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Review Draft

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Volume IV of V

NOTICE

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16. ABSTRACT
Scientific information is presented and evaluated relative to the health and welfare effects associated with exposure to ozone and other photochemical oxidants. Though not intended as a complete, detailed literature review, the document covers pertinent literature through 1983 and early 1984.

Data on health and welfare effects are emphasized, but additional information is provided for understanding the nature of the oxidant pollution problem and for evaluating the reliability of effects data as well as their relevance to potential exposures to ozone and other photochemical oxidants at concentrations occurring in ambient air. Separate chapters as presented on the following exposure-related topics pertaining to ozone and other photochemical oxidants: properties, chemistry, and measurement; concentrations typically found in ambient air; formation and transport once formed; and nature, source, measurement, and concentrations of precursors.

The specific areas addressed by chapters on health and welfare effects are the toxicological appraisal of effects of ozone and other oxidants; effects observed in controlled, human exposures; effects observed in field and epidemiological studies; effects on vegetation seen in field and controlled exposures; effects on natural and agroecosystems; and effects on nonbiological materials observed in field and chamber studies.

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CHAPTER 10
TOXICOLOGICAL EFFECTS OF OZONE AND OTHER PHOTOCHEMICAL OXIDANTS

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LIST OF ABBREVIATIONS

A-V	Atrioventricular
ACh	Acetylcholine
AChE	Acetylcholinesterase
AM	Alveolar macrophage
AMP	Adenosine monophosphate
ATPase	Adenosine triphosphatase
ATPS	ATPS condition (ambient temperature and pressure, saturated with water vapor)
BTPS	BTPS conditions (body temperature, barometric pressure, and saturated with water vapor)
CC	Closing capacity
C_{dyn}	Dynamic lung compliance
CHEM	Gas phase chemiluminescence
C_L	Lung compliance
C_{Lst}	Static lung compliance
CMP	Cytidine monophosphate
CNS	Central nervous system
CO	Carbon monoxide
COHb	Carboxyhemoglobin
COLD	Chronic obstructive lung disease
COMT	Catechol-o-methyl-transferase
CO_2	Carbon dioxide
CPK	Creatine phosphokinase
CV	Closing volume
D_L,	Diffusing capacity of the lungs
D_LCO	Carbon monoxide diffusion capacity of the lungs
DNA	Deoxyribonucleic acid
E	Elastance
ECG, EKG	Electrocardiogram
EEG	Electroencephalogram
ERV	Expiratory reserve volume
FEF_{max}	The maximal forced expiratory flow achieved during an FVC.
FEF	Forced expiratory flow

LIST OF ABBREVIATIONS (continued)

$FEF_{200-1200}$	Mean forced expiratory flow between 200 ml and 1200 ml of the FVC [formerly called the maximum expiratory flow rate (MEFR)].
$FEF_{25-75\%}$	Mean forced expiratory flow during the middle half of the FVC [formerly called the maximum mid:expiratory flow rate (MMFR)].
$FEF_{75\%}$	Instantaneous forced expiratory flow after 75% of the FVC has been exhaled.
FEV	Forced expiratory volume
FIVC	Forced inspiratory vital capacity
f_R	Respiratory frequency
FRC	Functional residual capacity
FVC	Forced vital capacity
G	Conductance
G-6-PD	Glucose-6-phosphate dehydrogenase
Gaw	Airway conductance
GMP	Guanosine monophosphate
GS-CHEM	Gas-solid chemiluminescence
GSH	Glutathione
GSSG	Glutathione disulfide
Hb	Hemoglobin
Hct	Hematocrit
HO·	Hydroxy radical
H_2O	Water
IC	Inspiratory capacity
IRV	Inspiratory reserve volume
IVC	Inspiratory vital capacity
$\bar{K}_o$	Average mucous production rate per unit area
LDH	Lactate deyhydrogenase
LD_{50}	Lethal dose (50 percent)
LM	Light microscopy
LPS	Lipopolysaccharide
MAO	Monamine oxidase

LIST OF ABBREVIATIONS (continued)

MAST	KI-coulometric (Mast meter)
max $\dot{V}_E$	Maximum ventilation
max $\dot{V}O_2$	Maximal aerobic capacity
MBC	Maximum breathing capacity
MEFR	Maximum expiratory flow rate
MEFV	Maximum expiratory flow-volume curve
MetHb	Methemoglobin
MMFR or MMEF	Maximum mid-expiratory flow rate
MNNG	N-methyl-N'-nitrosoguanidine
MPO	Myeloperoxidase
MVV	Maximum voluntary ventilation
NBKI	Neutral buffered potassium iodide
$(NH_4)_2SO_4$	Ammonium sulfate
NO_2	Nitrogen dioxide
NPSH	Non-protein sulfhydryls
ΔN_2, dN_2	Nitrogen washout
O_2	Oxygen
O_2^-	Oxygen radical
O_3	Ozone
$P(A-a)O_2$	Alveolar-arterial oxygen pressure difference
PABA	para-aminobenzoic acid
P_ACO_2	Alveolar partial pressure of carbon dioxide
$PaCO_2$	Arterial partial pressure of carbon dioxide
PAN	Peroxyacetyl nitrate
P_AO_2	Alveolar partial pressure of oxygen
PaO_2	Arterial partial pressure of oxygen
PEF	Peak expiratory flow
PEFV	Partial expiratory flow-volume curve
PG	Prostaglandin
pH_a	Arterial pH
PHA	Phytohemagglutinin
P_L	Transpulmonary pressure
PMN	Polymorphonuclear leukocyte

LIST OF ABBREVIATIONS (continued)

PPD	Purified protein derivative
P_{st}	Static transpulmonary pressure
PUFA	Polyunsaturated fatty acid
R	Resistance to flow
Raw	Airway resistance
RBCs	Red blood cells
R_{coll}	Collateral resistance
R_L	Total pulmonary resistance
RQ, R	Respiratory quotient
R_{ti}	Tissue resistance
RV	Residual volume
SaO_2	Arterial oxygen saturation
SCE	Sister chromatid exchange
Se	Selenium
SEM	Scanning electron microscopy
SGaw	Specific airway conductance
SH	Sulfhydryls
SOD	Superoxide dismutase
SO_2	Sulfur dioxide
SPF	Specific pathogen-free
SRaw	Specific airway resistance
STPD	STPD conditions (standard temperature and pressure, dry)
TEM	Transmission electron microscopy
TGV	Thoracic gas volume
TIC	Trypsin inhibitor capacity
TLC	Total lung capacity
TRH	Thyrotropin-releasing hormone
TSH	Thyroid-stimulating hormone
TV	Tidal volume
UFA	Unsaturated fatty acid
UMP	Uridine monophosphate
UV	Ultraviolet photometry

LIST OF ABBREVIATIONS (continued)

$\dot{V}_A$	Alveolar ventilation
$\dot{V}_A/\dot{Q}$	Ventilation/perfusion ratio
VC	Vital capacity
$\dot{V}CO_2$	Carbon dioxide production
V_D	Physiological dead space
$\dot{V}_D$	Dead-space ventilation
$V_{D\ anat}$	Anatomical dead space
$\dot{V}_E$	Minute ventilation
$\dot{V}_E$	Expired volume per minute
$\dot{V}_E$	Inspired volume per minute
V_L	Lung volume
$\dot{V}_{max}$	Maximum expiratory flow
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_2$, $\dot{Q}O_2$	Oxygen consumption
^{125}I	Irradiated iodine
5-HT	5-hydroxytryptamine
6-P-GD	6-phosphogluconate dehydrogenase

MEASUREMENT ABBREVIATIONS

g	gram
hr/day	hours per day
kg	kilogram
kgm/min	kilogram-meter/min
L/min	liters/min
ppm	parts per million
mg/kg	milligrams per kilogram
mg/m^3	milligrams per cubic meter
min	minute
ml	milliliter
mm	millimeter
$\mu g/m^3$	micrograms per cubic meter
μm	micrometers
μM	micromole
sec	second

10. TOXICOLOGICAL EFFECTS OF OZONE AND OTHER PHOTOCHEMICAL OXIDANTS

10.1 INTRODUCTION

This chapter discusses the effects of ozone on experimental animals. Carefully controlled studies of the effects of ozone on animals are particularly important in elucidating subtle effects not easily found in man through epidemiological studies and in identifying chronic toxicity not apparent from short-term controlled human exposures. Animal studies allow investigations into the effects of ozone exposure over a lifetime, uncomplicated by the presence of other pollutants. In the animal experiments presented here, a broad range of ozone concentrations have been studied, and many of the effects of ozone are reasonably well described. In general, emphasis has been placed on recent studies at 1960 μg/m^3 (1 ppm) of ozone or less. Higher concentrations have been cited when the data add to an understanding of mechanisms. Concentrations of 1 ppm or greater cannot be studied ethically in man because of the toxicity of even short-term exposures.

Primary emphasis has been placed on the effects of ozone on the respiratory tract, but extrarespiratory system effects have now been noted and are documented in this chapter. Most of these studies utilize invasive methods that require sacrifice of the animals on completion of the experiment; thus, the studies would be impossible to perform in human subjects. Noninvasive methods of examining most of these endpoints are not readily available.

Emphasis has been placed on the more recent literature published after the prior criteria document (U.S. Environmental Protection Agency, 1978); however, older literature has been reviewed again in this chapter. As more information on the toxicity of ozone becomes available, a better understanding of earlier studies is possible and a more detailed and comprehensive picture of ozone toxicity is emerging. The literature used in developing this chapter is set out in a series of tables. Not all of the literature cited in the tables appears in the detailed discussion of the text, but citations are provided to give the reader more details on the background from which the text is drawn.

In selecting studies for consideration, a detailed review of each paper has been completed. Technical considerations for inclusion of a specific study included an evaluation of the exposure methods; the analytical method used to determine the chamber ozone concentration; the calibration of the ozone monitoring equipment and the analytical methods used (wherever possible); the species, strain, age and physical characteristics of the the subject animals; the technique used for obtaining samples; and the appropriateness of the technique used to measure the effect. In interpreting the results, the number of animals used, the appropriateness and results of the statistical analysis, the degree to which the results conform with past studies, and the appropriateness of the interpretation of the results are considered. No additional statistical analysis beyond that reported by the author has been undertaken. Unless otherwise stated, all statements of effects in the text are statistically significant at $p \leq 0.05$. Many reports, especially in the older literature, do not present sufficient information to permit the judgments described above. However, should a particular study not meet all of these criteria, but provide reasonable data for consideration, a disclaimer is provided in the text and/or tables.

In this chapter, a discussion of the regional respiratory dosimetry of ozone in common laboratory animal species is presented and compared to human dosimetry. Morphological alterations of the lungs of animals exposed to O_3 are next described, followed by the effects of ozone on the pulmonary function of animals. The biochemical alterations observed in the ozone-exposed animals are then related to morphological changes and to potential mechanisms of toxicity and biochemical defense mechanisms. The protective role of dietary factors, such as vitamins E and C, in animals is discussed with consideration of potential roles in humans. It should be stressed, however, that no evidence for complete protection against ozone toxicity has been found for any factor, dietary or therapeutic. The effects of ozone on the defense mechanisms of the lung against respiratory infectious agents are discussed using the infectivity model system and effects on alveolar macrophages as examples of experimental evidence. This section is followed by a discussion of ozone tolerance in animals. Last, the effects of ozone on a number of extrarespiratory organ systems are discussed to provide insight into potential effects of ozone inhalation beyond those now well documented in the respiratory system.

A brief discussion of the available literature on the effects of other oxidants likely to occur in polluted air as a result of photochemical reactions or other sources of pollution is presented. Peroxyacetyl nitrate, hydrogen peroxide, and automobile exhaust are the principal pollutants studied in these experiments. This section is short because of the general lack of information in this area, but its brevity does not necessarily reflect a general lack of importance.

A summary is provided for all of the sections of the chapter to set the tone for a clearer understanding of the effects of ozone on animals. The major emphasis of this chapter is to provide evidence for the toxicity of ozone which can not, ethically or practically, be obtained from the study of human subjects. The overall health effects of ozone can be judged from three types of studies: animal exposures, controlled human exposures, and epidemiological studies of adventitious human exposures. No single method alone is adequate for an informed judgment, but together they provide a reasonable estimate of the human health effects of ozone on man.

10.2 REGIONAL DOSIMETRY IN THE RESPIRATORY TRACT

A major goal of environmental toxicological studies on animals is the eventual quantitative extrapolation of results to man. One type of information necessary to obtain the goal is dosimetry, which is the specification of the quantity of inhaled material, in this instance ozone (O_3), absorbed by specific sites in animals or man. This information is needed because the local dose (quantity of O_3 absorbed per unit area), along with cellular sensitivity, determines the type and extent of injury. At this time, only dosimetry is sufficiently advanced for discussion here. Until both elements are advanced, quantitative extrapolation cannot be conducted.

At present, there are two approaches to dosimetry, experimental and deterministic mathematical modeling. Animal experiments have been carried out to obtain direct measurements of O_3 absorption; however, experimentally obtaining local lower respiratory tract (tracheobronchial and pulmonary regions) uptake data is currently extremely difficult. Nevertheless, experimentation is important in assessing concepts and hypotheses, and in validating mathematical models that can be used to predict local doses.

Because the factors affecting the transport and absorption of O_3 are general to all mammals, a model that uses appropriate species and/or disease-specific anatomical and ventilatory parameters can be used to describe O_3 absorption in the species and in different-sized, aged, or diseased members of the same species. Models may also be used to explore processes or factors which cannot be studied experimentally, to identify areas needing additional research, and to test our understanding of O_3 absorption in the respiratory tract.

10.2.1 Absorption in Experimental Animals

There have been very few experiments in which measurements of the regional uptake of O_3 or other reactive gases have been determined. Of the several results published, only one is concerned with the uptake of O_3 in the lower respiratory tract; the others deal with nasopharyngeal uptake.

10.2.1.1 Nasopharyngeal Absorption. Nasopharyngeal removal of O_3 lessens the quantity of O_3 delivered to the lung and must be accounted for when estimating the O_3 dose responsible for observed pulmonary effects. Vaughan et al. (1969) exposed the isolated upper airways of beagle dogs to O_3 at a continuous flow of 3.0 L/min and collected the gas below the larynx in a plastic (mylar) bag. One-hundred percent uptake by the nasopharynx was reported for concentrations of 0.2 to 0.4 ppm. Using a different procedure, Yokoyama and Frank (1972) observed 72 percent uptake at 0.26 to 0.34 ppm (3.5 L/min to 6.5 L/min flow rate). They also replicated the procedure of Vaughan et al. and found that O_3 was absorbed on the mylar bag wall. This may account for the difference between the observations of Yokoyama and Frank (1972) and of Vaughan et al. (1969).

Yokoyama and Frank (1972) also observed a decrease in the percent uptake due to increased flow rate as well as to increased O_3 concentration. For example, with nose breathing and an O_3 concentration of 0.26 to 0.34 ppm, the uptake decreased from 72 percent to 37 percent for a flow rate increase from 3.5 to 6.5 to 35 to 45 L/min. An increase in concentration from 0.26 to 0.34 to 0.78 to 0.80 ppm decreased nose breathing uptake (3.5 to 6.5 L/min flow rate) from 72 percent to 60 percent. Their data, however, indicate that the tracheal concentration increases with increased nose or mouth concentrations. They also demonstrated that the concentration of O_3 reaching the trachea depends heavily on the route of breathing. Nasal uptake significantly exceeded oral uptake at flow rates of both 3.5 to 6.5 and 35 to 45 L/min. For a given flow rate, nose breathing removed 50 to 68 percent more O_3 than did mouth breathing.

Moorman et al. (1973) compared the loss of O_3 in the nasopharynx of acutely and chronically exposed dogs. Beagles chronically exposed (18 months) to 1 to 3 ppm of O_3 under various daily exposure regimes had significantly higher tracheal concentrations of O_3 than animals tested after 1 day of exposure to corresponding regimes. Moorman et al. (1973) suggested that the differences were due to physiochemical alterations of the mucosal lining in the chronically exposed beagles. When dogs were exposed for 18 months to 1 ppm for 8 hr a day, they had significantly lower tracheal values than those continuously exposed. The average tracheal concentration (0.01 ppm) for the acutely exposed group, however, was not significantly different from that (0.023 ppm) of the 8 hr/day chronic exposure group, when the relative insensitivity of the Mast O_3 meter (unmodified) used to measure the responses is taken into account. Thus, at levels of 1.0 ppm or less, there is no significant evidence that chronic exposure would result in tracheal O_3 concentrations significantly greater than those observed with acute exposure.

Nasopharyngeal removal of O_3 in rabbits and guinea pigs was studied by Miller et al. (1979) over a concentration range of 0.1 to 2.0 ppm. The tracheal O_3 concentration in these two species was markedly similar at a given inhaled concentration and was linearly related to the chamber concentration that was drawn unidirectionally through the isolated upper airways. Ozone removal in the nasopharyngeal region was approximately 50 percent in both species over the concentration range of 0.1 to 2.0 ppm. The positive correlation between the tracheal and chamber concentrations is in agreement with Yokoyama and Frank (1972).

10.2.1.2 Lower Respiratory Tract Absorption. Morphological studies on animals suggest that O_3 is absorbed along the entire respiratory tract; it penetrates further into the peripheral nonciliated airways as inhaled O_3 concentrations increase (Dungworth et al., 1975b). Lesions were found consistently in the trachea and proximal bronchi and between the junction of the conducting airways and the gaseous exchange area; in both regions, the severity of damage decreases distally. In addition, several studies have reported the most severe or prominent lesions to be in the centriacinar region (see section 10.3).

No experiments determining O_3 tissue dose at the generational or regional level have been reported; however, there is one experiment concerned with the uptake of O_3 by the lower respiratory tract. Removal of O_3 from inspired air by the lower airways was measured by Yokoyama and Frank (1972) in dogs that were mechanically ventilated through a tracheal cannula. In the two ranges of O_3 concentrations studied, 0.7 to 0.85 ppm and 0.2 to 0.4 ppm, the rate of uptake was found to vary between 80 and 87 percent when the tidal volume was kept constant and the respiratory pump was operated at either 20 or 30 cycles/min. This estimate of uptake applies to the lower respiratory tract as a whole; it does not describe uptake of O_3 by individual regions or generations.

10.2.2 Ozone Dosimetry Models

10.2.2.1 Modeling Nasal Uptake. LaBelle et al. (1955) considered the absorption of gases in the nasal passages to be similar to absorption on wetted surfaces of distillation equipment and scrubbing towers and applied the theory and models of these devices to the nasal passages of rats. By associating biological parameters of rats with the chemical engineering device parameters of the model, they calculated the percent of penetration of several gases to the lung. They concluded that Henry's law constant is the major variable in determining penetration. Based on these calculations, The National Academy of Sciences (NAS, 1977) concluded that the model predicts 99 percent penetration for O_3. This is much more than that measured by Yokoyama and Frank (1972) or by Miller et al. (1979). NAS (1977) discusses several possible reasons for the differences, but considers the major factor to be that the model does not account for the reactions of O_3 in the mucus and epithelial tissue.

Aharonson et al. (1974) developed a model for use in analyzing data from experiments on the uptake of vapors by the nose. The model was based on the assumption of quasi-steady-state flow, mass balance, and that the flux of a trace gas at the air-mucus interface is proportional to the gas-phase partial pressure of the trace gas and a "local uptake coefficient" (Aharonson et al., 1974). The model was applied to data from their own experiments on the removal of acetone and ether in dog noses. They also applied the model to the O_3 uptake data of Yokoyama and Frank (1972) and concluded that the uptake coefficient (average mass transfer coefficient) for O_3, as well as for the other gases considered, increases with increasing air flow rate.

10.2.2.2 Lower Respiratory Tract Dosimetry Models. There are two models for which published results are available. The model of McJilton et al. (1972) has never been formally published; however, its features have been discussed in detail (National Academy of Sciences, 1977; Morgan and Frank, 1977) and simulation results for O_3 absorption in each generation of the human lower respiratory tract are available (National Academy of Sciences, 1977; Morgan and Frank, 1977). A detailed description of the formulation of the mathematical model of Miller and co-workers is found in Miller (1977) and an overview is given in Miller (1979). Results of simulations of the respiratory tract absorption of O_3 in humans, rabbits, and guinea pigs are in Miller (1977, 1979), and Miller et al. (1978).

Because both models were developed to simulate the local absorption of O_3, they have much in common. The descriptions of O_3 transport and absorption in the lumen are based on a one-dimensional differential equation relating axial convection, axial dispersion or diffusion, and the loss of O_3 by absorption at the gas-liquid interface. The use of a one-dimensional approximation has been very common in modeling the transport of gases such as O_2, N_2, and others in the lower respiratory tract (see Scherer et al., 1972; Paiva, 1973; Chang and Farhi, 1974; Yu, 1975; Pack et al., 1977; Bowes et al., 1982). The approximation is appropriate for O_3 as well.

McJilton et al. considered only molecular diffusion for O_3 transport in the liquid lining the airway (National Academy of Sciences, 1977; Morgan and Frank, 1977). In addition to this process, Miller et al. (1978) included the effect of chemical reactions on O_3 transport in the liquid lining. By using their respective assumptions, equations based on mass balance considerations were developed for O_3 transport in the lining. The liquid-phase equations were coupled to the gas-phase equations based on physical considerations: continuity of O_3 transfer across the gas-liquid interface was required and the gas and liquid phase interfacial concentrations were related by Henry's law constant.

Airway or morphometric zone models such as those of Weibel (1963) and Kliment (1973) were used in both models to define the lengths, radii, surface areas, cross-sectional areas, and volumes of the airways and air spaces of each generation or zone. A sinusoidal breathing pattern was used; however, dimensions were held constant throughout the breathing cycle. The physical properties of the liquid lining were assumed to be those of water. The lining thickness depended on generation or zone, being thicker in those with lower numbers than in those with higher numbers.

The flux of O_3 from the lumen to the liquid lining was defined in terms of a mass-transfer coefficient which depended on gas-phase and liquid-phase transfer coefficients. McJilton et al. (National Academy of Sciences, 1977) made the assumption that the mass transfer was liquid-phase controlled and estimated the transfer coefficient from empirical data on the physical properties (not chemical) of the liquid lining and of O_3. In the Miller model (Miller, 1977) the radial dependence of the luminal O_3 concentration was assumed to vary quadratically with the radius. From this formulation, the gas-phase mass transfer was determined. It was combined with the liquid-phase mass transfer coefficient (which depended on the chemical and physical properties of the liquid and of O_3) to obtain the overall transfer coefficient. No assumption was necessary or made about which phase, if either, controlled the transfer.

Ozone concentration in tissue and at the liquid-tissue interface was assumed to be zero (Miller, 1977; National Academy of Sciences, 1977). The National Academy of Sciences (1977) and Miller (1977) believe this boundary condition means that O_3 reacts (chemically) instantaneously when it reaches the tissue. Miller et al. (1978) define the tissue dose as that quantity of O_3 per unit area reacting with the tissue at the liquid-tissue interface.

There are major differences in the two models. Ozone is known to react chemically with constituents of the liquid lining. This factor was not included in the McJilton et al. model. Chemical reactions were taken into account in the mucous-serous lining in the Miller model. The inclusion resulted in significant differences between the tissue dose pattern curves in the tracheobronchial region predicted by the two models. The McJilton et al. model predicts a dose curve (equivalent to a tissue dose curve because of no mucous reactions) in the conductive zone that has its maximum at the trachea and decreases distally to the thirteenth or fourteenth generation (see Figure 7-5 in National Academy of Sciences, 1977). By contrast, the Miller model predicts the tissue dose to be a minimum at the trachea and to increase distally to the pulmonary region.

Miller and co-workers took into account the reaction of O_3 with the unsaturated fatty acids (UFA) and amino acids in the mucous-serous lining. Reactions of O_3 with other components (such as carbohydrates) were not included in the model because of insufficient information (Miller, 1977; Miller et al., 1978). The O_3-UFA and O_3-amino acid reactions were assumed fast enough so that an instantaneous reaction scheme based on that outlined in Astarita (1967) could be used. The scheme required the specification of the production rate of the UFA and amino acids in each mucous-lined generation. These rates were estimated by using tracheal mucous flow data, the surface area of the tracheobronchial region, the concentrations of the specific reactants known to react with O_3, and the assumption that the production rate decreased distally (Miller, 1977).

Although the instantaneous reaction scheme is a good preliminary approach to treating O_3 reactions in the mucous-serous lining, its use is not completely justifiable. Second-order rate constants of O_3 with some of the mucous UFA indicate that although they are large (Razumovskii and Zaikov, 1972), they are less than the diffusion-limited rates necessary for the instantaneous reactions and scheme. Experimental evidence (Mudd et al., 1969) suggests that the reactions of O_3 with amino acids are very rapid. Rate constants for these reactions and others are not known; thus, the information available is scanty, which makes the specification of a reaction mechanism or reaction scheme difficult and assumptions necessary.

The Miller model also took into account effective axial dispersion in the airways by using an effective dispersion coefficient based on the results of Scherer et al. (1975). McJilton et al. did not take this factor into account (Morgan and Frank, 1977). However, this may not be an important difference in the two models. Pack et al. (1977) and Engle and Macklem (1977) reported results that indicate an insensitivity of airway concentrations to the effective dispersion coefficient.

10.2.3 Predictions of Lower Respiratory Tract Ozone Dosimetry Modeling

The predictions of lower respiratory tract dosimetry models are reviewed by illustrating the results of simulations, by comparing predictions to experimental observations, and by describing a possible use for dosimetry modeling.

The following discussion of modeling results of lower respiratory tract absorption is based on simulations using the Miller model. This is because the model includes the important effects of O_3 reactions in the mucous-serous lining and because simulations of O_3 absorption in laboratory animals are available.

Simulations of O_3 absorption in different animals can be carried out by modifying input parameters of the computer program that solves the mathematical equations. These input parameters, which characterize an animal, include the number and dimensions of the airways, tidal volume, and length of time of one breath. The airway and alveolar dimensions of Weibel (1963) were used for the simulation of O_3 uptake in humans. For the rabbit and guinea pig, Miller and co-workers used the morphometric zone models of Kliment (1973). The zone model is a less detailed model than the generationally based airway model of Weibel (1963). In general, more than one generation in man corresponds to one zone in an animal. However, each zone is characterized by the number of airways and their lengths and diameter. The zone models were used because they were the only complete (tracheobronchial and pulmonary regions) "airway" models available at the time. Also, similar zone models, such as that of Landahl (1950), have been used successfully in human aerosol deposition studies.

To illustrate simulation results, three aspects of the simulations by Miller and co-workers are considered: 1) the effect of various tracheal concentrations on the tissue dose pattern (tissue dose as a function of zone or generation) in guinea pigs and rabbits; 2) the similarity between the dose patterns of guinea pigs, rabbits, and humans; and 3) the effect on simulations due to the uncertainty of the knowledge of the production rates of the mucous-serous components that react with O_3 and of the knowledge of the mucous-serous thickness.

10.2.3.1 Illustration of Dosimetry Simulations. Figure 10-1 is a set of plots of the tissue dose for one breath versus zone for various tracheal O_3 concentrations for rabbit and guinea pig simulations. (Ambient concentrations would be roughly twice the tracheal concentration according to Miller et al., 1979.) All curves have the same general characteristics. Independent of the inhaled concentration, the model predicts that the first surfactant-lined zone (first non-mucous-lined or first zone in the pulmonary region), zone 6, receives the maximum dose of O_3. Although the model predicts uptake of O_3 by respiratory tissue (zones 6, 7, and 8) for all tracheal concentrations studied (62.5 to 4000 $\mu g/m^3$), the penetration of O_3 to the tissue in the airways lined by mucus depended on the tracheal concentration and the specific animal species. For example, as illustrated in Figure 10-1 for the tracheal O_3 concentration of 1000 $\mu g/m^3$, no O_3 reaches the airway tissue of the rabbit until zone 3, whereas O_3 is predicted to penetrate to the guinea pig airway tissue in all zones. However, at the two lowest tracheal concentrations plotted, 250 and 62.5 $\mu g/m^3$, no penetration occurs until zones 4 and 6, respectively, for both animals.

The similarity of the predicted dose patterns in rabbits and guinea pigs extends to the simulation of O_3 uptake in humans. Figure 10-2 compares the tissue dose for the three species for a tracheal concentration of 500 $\mu g/m^3$ (0.26 ppm). Because of the different airway models used, the plot of the data for the laboratory animals differs from that of Figure 10-1. In Figure 10-2 the guinea pig and rabbit tissue dose are plotted in the form of a histogram. This allows a plot of the human data, even though there is more than one generation corresponding to one zone.

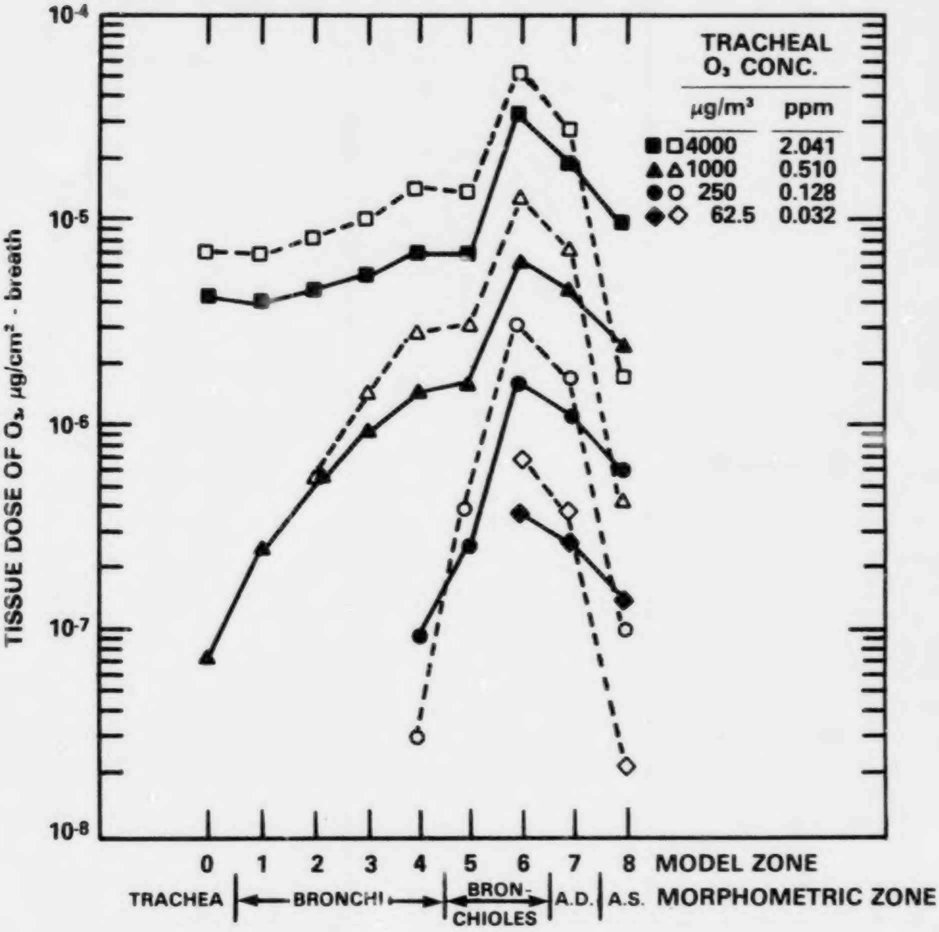

Figure 10-1. Predicted tissue dose for several tracheal O_3 concentrations for rabbit (open symbols) and guinea pig (closed symbols). See text for details. (A.D. = alveolar duct; A.S. = alveolar sac).
Source: Adapted from Miller et al. (1978).

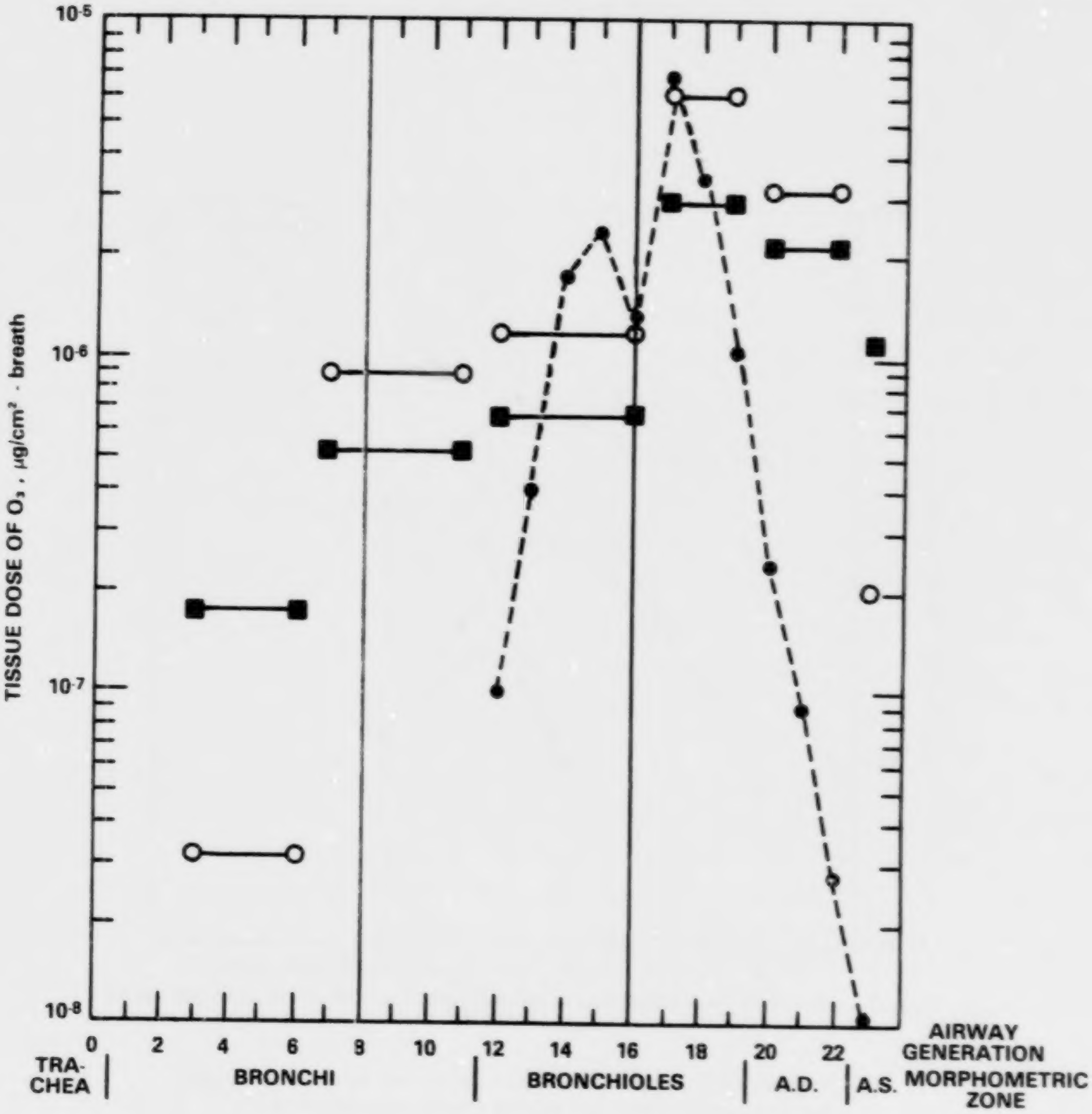

Figure 10-2. Tissue dose versus morphometric zone for rabbit (○) and guinea pig (■); and tissue dose versus airway generation for human (-●-) at a tracheal O_3 concentration of 500 μg/m³ (0.26 ppm). See text for details. (A.D. = alveolar duct; A.S. = alveolar sac)
Source: Adapted from Miller et al. (1978).

The dose patterns of the three species peak at the first surfactant-lined zone (6) or in generation 17 (which is in zone 6). Also, O_3 penetrates to the tissue everywhere in the pulmonary region (zones > 5 and generations > 16); however, O_3 is not predicted to penetrate to the tissue before zone 3 for the rabbit and guinea pig or before zone 5 (generations 12-16) for man.

The characteristics of the ozone tissue dose pattern for the three species, as discussed here, are general to the simulations presented by Miller and co-workers (Miller, 1977; Miller et al., 1978; Miller, 1979): 1) the maximum tissue dose occurs in the first surfactant-lined zone or generation; 2) O_3 penetrates to tissue everywhere in the pulmonary region (zones > 5), decreasing distally from the maximum; and 3) the onset of O_3 penetration to mucous-lined tissue, as well as dose in general, depends on tracheal O_3 concentration, animal species, and the breathing pattern. These general characteristics of tissue dose pattern are independent of the two airway models used. Whether or not this would be so if more recent and detailed airway models (e.g., Phalen et al., 1978) were used or if O_3 uptake were simulated in other species would be of interest in understanding O_3 absorption.

Sensitivity studies were carried out with two major parameters, the average mucous production rate per unit area ($\bar{K}_0$) and the mucous-serous thickness (Miller, 1977; Miller et al., 1978; Miller, 1979). The parameter $\bar{K}_0$ is related to the chemical reaction scheme used by Miller and co-workers; as $\bar{K}_0$ increases, so does the reactivity. The study showed that if $\bar{K}_0$ overestimated the correct value, there would be no difference in the predicted respiratory bronchiolar (zone 6 or generation 17) dose for any of the three species studied. If $\bar{K}_0$ underestimated the correct value, the results were not as clear; they depended on the tracheal concentration and species. The guinea pig and rabbit were the least sensitive species; they required a twenty-five and a fifty-fold underestimate of $\bar{K}_0$ for 325 and 750 $\mu g/m^3$ tracheal O_3 concentration, respectively, before significant variations in respiratory bronchiolar tissue dose occurred. Significant differences occurred in the human dose for a ten- and a twenty-five-fold underestimate (corresponding to 325 and 750 $\mu g/m^3$, respectively). Decreasing $\bar{K}_0$ also allowed more O_3 to penetrate to the tissue in the conducting airways, and increasing $\bar{K}_0$ resulted in less O_3 penetrating to the conducting airway tissue. In the other sensitivity study, a 25 percent increase in the mucous lining thickness decreased the conducting airway dose but had no effect on respiratory region tissue dose (see Figures 2 and 8 and discussion in Miller, 1977).

10.2.3.2 Comparison of Simulations to Experimental Data. There are no quantitative experimental observations with which to compare the results of modeling the local uptake of O_3 in the lower respiratory tract. Yokoyama and Frank (1972) observed 80 to 87 percent uptake of O_3 by the lower respiratory tract of dogs. Miller et al. (1978) predict a 60 percent uptake for humans; however, because of differences between two species, comparing the two results is most likely inappropriate.

Morphological studies in animals report damage throughout the lower respiratory tract. Major damage, and in some cases the most severe damage, is observed to occur at the junction between the conducting airways and the gas exchange region, and to decrease distally (see Section 10.3.1.1). Of interest is that for the animals simulated by Miller and co-workers, the maximum tissue dose of O_3 occurs in this junction and decreases distally. Thus, in the pulmonary region, the model results are in qualitative agreement with experimental observations.

Damage is also observed in the trachea and bronchi of animals (see Sections 10.3.1.1.1.2 and 10.3.1.1.1.3). In the animals modeled, the Miller model either predicts significantly less tissue dose in these regions compared to the dose in the first zone of the pulmonary region or it predicts no penetration to the tissue in the upper portion of the conducting airways (see Figure 10-2). A factor complicating an understanding of the above is the possibility of O_3 reaction products being toxic. Other factors confounding interpretation are cell sensitivity and animal differences. Also, much of the reported damage in the trachea and bronchi is associated with the cilia of ciliated cells, which in the Miller model are not part of the tissue. The cilia extend into the hypophase (perciliary) portion of the mucous-serous layer, and the Miller dosimetry model does not distinguish the cilia of the ciliated cells as a separate component of this layer. Thus, zero or relatively low predicted tissue dose should not be interpreted as predicting no cilia damage. Likewise, the frequent reporting of cilia being damaged following O_3 exposure should not be interpreted necessarily as an indication of O_3 tissue dose since the definition of tissue applied does not include cilia.

10.2.3.3 A Use of Predicted Doses. Miller (1979) discusses how doses predicted by the model can be used to estimate comparable exposure levels that produce the same dose in different species or different members of the same species for use in comparing toxicological data. The procedure is to simulate tissue dose for several species for the same time (Miller, 1979) for a range of tracheal O_3 concentrations. The doses for a specific zone or generation, for each species, are plotted versus tracheal or ambient O_3 concentration. By using such plots and information on nasopharyngeal removal (Miller et al., 1979), the ambient concentration necessary to produce the same dose in different species can be estimated (see Miller, 1979). Also, the relative quantity of O_3 delivered to a zone or generation in a given species for the same time span and ambient concentration can be predicted from the same graph. If the same biological parameters have not been measured in these species at dose-equivalent exposure levels, the procedure can be used to scale data and to design new studies to fill gaps in the current data base.

10.3 EFFECTS OF OZONE ON THE RESPIRATORY TRACT

10.3.1 Morphological Effects

The many similarities and differences in the structure of the lungs of man and experimental animals were the subject of a recent workshop entitled Comparative Biology of the Lung: Morphology, which was sponsored by the Lung Division of the National Institute of Blood, Heart, and Lung Diseases (National Institutes of Health, 1983). These anatomical differences complicate but do not necessarily prevent qualitative extrapolation of risk to man. Moreover, because the lesions due to O_3 exposure are similar in many of the species studied (see Table 10-1), it appears likely that many of the postexposure biological processes of animals could also occur in man.

10.3.1.1 Sites Affected. The pattern and distribution of morphological lesions are similar in the species studied. Their precise characteristics depend on the location (distribution) of sensitive cells and on the type of junction between the conducting airways and the gaseous exchange area.

The upper or extrathoracic airways consist of the nasal cavity, pharynx, larynx, and cervical trachea. Except for a few sites, the lining epithelium is ciliated, pseudostratified columnar, with mucous (goblet) cells; it rests on a lamina propria or submucosa that contains numerous mucous, serous, or mixed glands and vascular plexi. Sites with differing structure include the vestibule of the nasal cavity and portions of the pharynx and larynx, which tend to have stratified squamous epithelium, and those portions of the nasal cavity lined by olfactory epithelium, which contain special bipolar neurons

TABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
µg/m³	ppm					
196	0.1	UV, NBKI	7 days, continuous	Two of six fed with "basal" vitamin E diet had increased centriacinar AMs (SEM, LM).	Rat	Plopper et al., 1979
392	0.2			Centriacinar accumulation of AMs, commonly in clumps of 3-5. Occasionally cilia were reduced in number, nonciliated cells, some reduction in height.		
196	0.1	UV, NBKI	7 days, continuous	Five of six fed E-deficient "basal" diet had centriacinar AMs and bronchiolar epithelial lesions (SEM). Four of six fed "basal" diet +11 ppm E had lesser but similar lesions. One of six fed "basal" diet +110 ppm E had lesser lesions.	Rat	Chow et al., 1981
392	0.2	MAST, NBKI	30 days, continuous	Increased lung volume, mean chord length, and alveolar surface area. Lung weight and alveolar number did not change. Decrease in lung tissue elasticity. Parenchyma appeared "normal" by LM.	Rat	Bartlett et al., 1974
392 686 980 1568	0.2 0.35 0.5 0.8	UV, NBKI	7 days, 8 hr/day	Respiratory bronchiolitis at all concentrations. Increased AMs. Bronchiolar epithelium both hyperplastic and hypertrophic. Increased alveolar type 2 cells. Random foci of short, blunt cilia or absence of cilia (LM, SEM, TEM).	Monkey (Rhesus and Bonnet)	Dungworth et al., 1975b
392 686	0.2 0.35	UV, NBKI	7 days, 8 hr/day	All exposed monkeys had LM & EM lesions. Trachea and bronchi had areas of shortened or less dense cilia. RBs had AM accumulation and cuboidal cell hyperplasia. Alveoli off RBs had AM accumulations and increased type 2 cells. RB walls of the 0.35-ppm group were often thickened due to mild edema and cellular infiltration.	Monkey (Bonnet)	Castleman et al., 1977
392 980 1568	0.2 0.5 0.8	UV, NBKI	7 days, 8 hr/day or 24 hr/day	Exposed groups gained less weight. Focal areas of missing or damaged cilia in trachea and bronchi. TB nonciliated (Clara) cells were shorter and had increased surface granularity and less smooth endoplasmic reticulum. Ciliated cells of TB had fewer cilia and focal blebs. Centriacinus had clusters of AMs and PMNs. Type 1 cells swollen and fragmented and type 2 cells frequently in pairs or clusters. Proximal IAS were minimally thickened. Lesions in 0.2 rats were mild (LM, SEM, TEM). Only slight differences between rats exposed continuously 24 hr/day compared to those exposed only 8 hr/day.	Rat	Schwartz et al., 1976

TABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued)

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
μg/m³	ppm					
392 980 1568	0.2 0.5 0.8	UV, NBKI	20, 50, or 90 days; 8 hr/day	Epithelial changes and PAM accumulations at 90 days were similar to 7-day exposures, but less severe. 0.5- and 0.8-ppm groups had increased centriacinar PAMs at all times. 0.2 ppm and controls could not be separated by "blind" LM examination, nor were there distinguishing EM changes. 90-day 0.8-ppm group had changed the terminal bronchiole/alveolar duct junction to terminal bronchiole/respiratory bronchiole/alveolar duct junctions. TBs had loss or shortened cilia. Nonciliated cells were flattened lumenal surfaces that occasionally occurred in clusters. Proximal alveoli of 20- and 90-day 0.8-ppm groups had thicker blood/air barriers.	Rat	Boorman et al., 1980
392 980 1960	0.2 0.5 1.0	ND, NBKI	4 days, 3 hr/day, exercised in a rotating case alternate 15 min	Exercised control mice have significantly smaller body weights. Both unexercised and exercised mice exposed to 0.5 or 1.0 ppm had smaller body weights and larger lung weight. Exercised mice exposed to 0.2 ppm also had larger lung weights. Other pathology not studied.	Mouse (male, 5 weeks old, ICR-JCL)	Fukase et al., 1978
392	0.2	CHEM	7, 14, 30, 60, 90 days; continuous	Short-term exposures produced a slight degree of tonsil epithelial detachment. Cell infiltration below the epithelium was slight. Long-term exposures caused slight edema of the lacunar epithelium which was destroyed or detached in places. Lymphocyte infiltration also occurred.	Rabbit	Ikematsu, 1978
1960	1.0		10 days, continuous	Tonsil epithelium had a high degree of detachment. Cell saturation occurred below the epithelium. Some protrusion of the tonsil into the oral cavity.		
9800	5.0		3 hr	Strong detachment of the tonsil epithelium. High degree of cell saturation below the epithelium, including lymphocyte infiltration around the blood vessels and swelling of the endothelial cells. Large amount of lymphocytes, viscous liquid, and detached epithelial cells in the tonsilar cavity.		

TABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued)

Ozone concentration $\mu g/m^3$	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
490	0.25	ND	6 weeks, 12 hr/day	Centriacinar alveoli had more type 1 and 2 alveolar epithelial cells and macrophages. Type 1 cells were smaller in volume, covered less surface, and thicker. Type 1 cell damage and occasional sloughing seen by TEM.	Rat	Barry et al., 1983
510 980 1960	0.26 0.50 1.0	MAST, NBKI	4.7-6.6 hr, endotracheal tube	Desquamation of ciliated epithelium. Focal swelling or sloughing of type 1 cells.	Cat	Boatman et al., 1974
588	0.3	NBKI	16 days, 3 hr/day	SEM, but not LM, showed swollen cilia with hemispheric extrusions and surface roughness. Some adhesion of severely injured cilia occurred. Small, round bodies were frequently noted, mainly in the large airways and proximal bronchioles. Luminal surfaces of the epithelium were often covered with a pseudomembrane. The surfaces of Clara cells showed swellings and round bodies. The surfaces of alveolar ducts and walls showed scattered areas of cytoplasmic swelling and attachment of round bodies. All responses were pronounced in vitamin E-deficient rats. Some rats had chronic respiratory disease.	Rat	Sato et al., 1976a
588	0.3	NBKI	28 weeks, 5 days/week, 3 hr/day	No morphological differences noted between vitamin E-deficient and vitamin E-supplemented groups with the use of SEM and TEM. Exposed and control rats had chronic respiratory disease.	Rat	Sato et al., 1980
588	0.3	UV	6 weeks, 5 days/week, 7 hr/day	Increased LDH positive cells stated to be type 2 cells.	Mouse	Sherwin et al., 1983
686 980 1372 1470 1960	0.35 0.50 0.70 0.75 1.00	ND	1, 2, 4, 5, 6 or 8 days, continuous	Dividing cells were labeled with tritiated thymidine and studied with autoradiographic techniques by using LM. All labeled cells increased and then decreased to near control levels within 4 days. Type 2 cells showed largest change in labeling index.	Rat	Evans et al., 1976b
686 980	0.35 0.50		4 days, continuous, followed by 0.50, 0.70, 0.75 or 1.00 for 1-4 days	Type 2 cells from groups showing adaptation to O_3 were exposed to higher concentrations. Groups exposed to low initial concentration of O_3 (0.35 ppm) did not maintain tolerance. Groups exposed to higher initial concentration (0.50 ppm) demonstrated tolerance.		

TABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued).

Ozone concentration $\mu g/m^3$	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
784	0.4	MAST	10 months, 5 days/week, 6 hr/day	All (exposed and control) lungs showed some degree of inflammatory infiltrate possibly due to intercurrent disease. A "moderate" degree of "emphysema" was present in 5 of the 6 exposed rabbits. Lungs of the 6th were so congested that visualization of the mural framework of the alveoli was difficult. Small pulmonary arteries had thickened tunica medias, sometimes due to edema, other times to muscular hyperplasia.	Rabbit (New Zealand)	P'an et al., 1972
784	0.4	NBKI	7 hr/day, 5 days/week, 6 weeks	Lung growth which follows pneumonectomy also occurred following both pneumonectomy and O_3 exposure.	Rabbit	Boatman et al., 1983
980	0.5	ND	2 to 6 hr	Centriacinar type 1 cells were swollen then sloughed. Type 2 cells were not damaged and spread over the denuded basement membrane. In some areas of severe type 1 cell damage, endothelial swelling occurred. Damaged decreased rapidly with distance from TB. Damage was most severe only in the most central 2-3 alveoli. Interstitial edema occasionally observed.	Rat (young males)	Stephens et al., 1974b
980 or 1568	0.5 or 0.8	UV, NBKI	7 continuous days; 2, 4, 6, 8, or 24 hr/day	Centriacinar inflammatory cells (mostly AMs) were counted in SEMs. Dose-related increase in inflammatory cell numbers except in the continuously (24-hr/day) 0.8-ppm exposed rats. Rats exposed 0.5 and 0.8 ppm 24 hr/day had the same intensity of effect.	Rat	Brummer et al., 1977
980	0.5	UV, NBKI	7, 21, and 35 days, continuous	Most severe damage at terminal bronchiole/alveolar duct junction. TB had focal hyperplastic nodules of nonciliated cells. Proximal alveoli had accumulations of macrophages and thickening of IAS by mononuclear cells at 7 days. At 35 days, changes much less evident, but increased type 2 cells.	Mouse (Swiss-Webster; 60 days old; 35-40 g)	Zitnik et al., 1978
980 1568	0.5 0.8	UV, NBKI	7, 28, or 90 days, continuous, 8 hr/day	Principal lesion was a "low-grade respiratory bronchiolitis" characterized by "intraluminal accumulations of macrophages and hypertrophy and hyperplasia of cuboidal bronchiolar epithelial cells." Conducting airway lesions not apparent by LM, but parallel linear arrays of uniform shortening and reduction of density of cilia by SEM. Kulschitzky-type cells appeared more numerous in exposed.	Monkey (Bonnet)	Eustis et al., 1981

ABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued)

Ozone concentration µg/m³	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
980 1568	0.5 0.8	UV, NBKI	7 days, 8 hr/day	All exposed monkeys had lesions. Lesions similar in 0.5- and 0.8-, less severe in 0.5-ppm exposure groups. Patchy areas of epithelium devoid of cilia in trachea and bronchi. Luminal surfaces of RB and proximal alveoli coated with macrophages, a few neutrophils and eosinophilis and debris. Nonciliated cuboidal bronchiolar cells were larger, more numerous, and sometimes stratified. Proximal alveolar epithelium thickened by increased numbers of type 2 cells. Progressive decrease in intensity of lesions from proximal to distal orders of RBs.	Monkey (Rhesus, adult)	Mellick et al., 1975, 1977
980 to 3920	0.5 to 2.0	UV, NBKI	7 days, 24 hr/day	Elevated collagen synthesis rates and histologically discernible fibrosis was present at all levels of O_3.	Rat	Last et al., 1979
				0.5 ppm Minimal or no thickening of walls or evidence of fibrosis. Increased number of cuboidal cells and macrophages present.		
				0.8-2.0 ppm: Moderate thickening of AD walls and associated IAS by fibroblasts, reticulin and collagen with narrowing of the ducts and alveoli. Thickening decreased with increased length of exposure.		
	0.5 to 1.5		14 days and 21 days, 24 hr/day	0.5 ppm Sometimes minimal thickening of alveolar duct walls with mildly increased reticulin and collagen.		
980	0.5 0.5 O_3 + H_2SO_4	CHEM, NBKI	6 months, 5 days/week, 6 hr/day	Only O_3 caused pulmonary lesions. Only LM histopathology, no SEM nor TEM. Rats did not have exposure-related pulmonary lesions, except 2 of 70 rats in the O_3 group, which had type 2 hyperplasia and focal alveolitis; 2 of 70 rats from the O_3 + H_2SO_4 group had slight hypertrophy and hyperplasia of bronchiolar epithelium. Guinea pigs exposed to O_3 or O_3 + H_2SO_4 had lesions "near" the TB. Epithelium was hypertrophied and hyperplastic. Macrophages were in centriacinar alveoli. Occasionally proliferation of type 2 cells. Trachea and bronchi had slight loss of cilia, reduction of goblet cells, and mild basal cell hyperplasia. Ozone alone had no effect on body weight gain; lung/body weight ratio; RBCs, hemoglobin, or hematocrit.	Rat and Guinea pig	Cavender et al., 1978

TABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued)

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
$\mu g/m^3$	ppm					
980	0.5 0.5 O_3 + H_2SO_4	UV, NBKI	3, 50, 90, or 180 days; continuous, plus 62 days postexposure, 24 hr/day	H_2SO_4 did not potentiate effects of O_3 alone. Fixed lung volumes were increased at 180 days, but decreased at 62 days postexposure. After 50, 90, 94 180 days all O_3 exposure rats had "bronchiolization of alveoli" or formation of an RB between the TB and ADs. Centriacinar inflammatory cells were significantly increased at all exposure times and after 62 days postexposure. TB lesions were qualitatively similar at 3, 50, 90, and 180 days. Cilia were irregular in number and length. Nonciliated secretory (Clara) cells had flattened apical protrusions and a blebbed granular surface. At 90, but not 180 days, small clusters of nonciliated cells were present in the TB. At 180 days, 2 of 12 rats had larger nodular aggregates of nonciliated cells which bulged into the lumen. Most rats had a very mild interstitial thickening of alveolar septa in the centriacinar region (LM, SEM, TEM).	Rat	Moore and Schwartz, 1981
1058 1725	0.54 0.88	ND	2, 4, 8, 12, or 48 hr	Severe loss of cilia from TB after 2 hr. TB surface more uniform in height than controls. Necrotic ciliate cells in TB epithelium and free in lumen after 6-12 hr of a 0.88-ppm exposure. Ciliated cell necrosis continued until 24 hr, when little evidence of further cell damage or loss was seen. Only minimal loss of ciliated cells in 0.5-ppm rat group. Nonciliated cells were "resistant" to injury from O_3 and hypertrophic at 72 hr. Damage to the first 2 or 3 alveoli after 0.54-ppm for 2 hr. Type 1 cell "fraying" and vesiculation. Damage was greater after 0.88 for 2 hr. "Basement lamina" denuded. Type 2 and 3 cells resistant. Macrophages accumulated in proximal alveoli. Endothelium appeared relatively normal. Repair started at 20 hr. Type 2 cells divide, cuboidal epithelium lines proximal alveoli where type 1 cells were destroyed. Continued exposure resulted in thickened alveolar walls and tissue surrounding TBs. Exposure for 8-10 hr followed by clean air until 48 hr resulted in a proliferative response (at 48 hr) about equal to that observed after continuous exposure (LM, SEM, TEM).	Rat	Stephens et al., 1974a
1058	0.54		6 months, 24 hr/day	No mention in either the results or discussion of the 6 months at 0.54-ppm group.		

TABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued)

Ozone concentration		Measurement^{a,b} method	Exposure duration and protocol	Observed effect(s)^{c}	Species	Reference
µg/m³	ppm					
1058 1725	0.54 0.88	ND	4 hr to 3 weeks	Ozone-exposed lungs heavier and larger than controls. Increased centriacinar macrophages. Hyperplasia of distal airway epithelium Increased connective tissue elements. Collagen-like strands formed bridges across alveolar openings. Fibrosis more pronounced in 0.88-ppm group.	Rat (month old)	Freeman et al., 1974
1764	0.9 O_3 + 0.9 NO_2		60 days	Respiratory distress during first month. Several rats died. Gross and microscopic appearance of advanced experimental emphysema as produced by NO_2 earlier (Freeman et al., 1972). Ozone potentiated effect of nitrogen dioxide.	Rat (month old)	
490	0.25 O_3 + 2.5 NO_2		6 months	"At 6 months the pulmonary tissue seemed quite normal." Proximal orders of ADs minimally involved.	Rat (month old)	
1176 2548	0.6 1.3	ND	1 or 2 days, 6 hr/day or 7 hr/day	Endothelial cells showed the most disruption. The lining membranes were fragmented. Cell debris was often present in the alveoli as well as the capillaries. Some disorganization of the cytoplasm of the large alveolar corner or wall cells was evident.	Mouse (young)	Bils, 1970
1372 1568	0.7 to 0.8	UV, NBKI	7 days, continuous	*In situ* cytochemical studies of lungs from O_3 exposed and control rats. Ozone-exposed rats had increased acid phosphatase, both in lysosomes and in the cytoplasm, in nonciliated bronchiolar (Clara) cells, alveolar macrophages, type 1 and 2 cells, and fibroblasts.	Rat	Castleman et al., 1973a
1372	0.7	ND	24 hr, continuous	Exposure end: General depletion of cilia from TB surface. Nonciliated cells were shorter and contained fewer dense granules, less SER, and more free ribosomes. Post exposure: (0-4 days) TB returned towards normal.	Rat	Evans et al., 1976a

TABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued)

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
μg/m^3	ppm					
1568	0.8	UV, NBKI	6, 10, 20 days exposure, 24 hr/day or 20 days exposure + 10 days postexposure	SEM of distal trachea and primary bronchi: 6 days: Cilia of variable length. 10 days: Marked loss of cilia. Very few cells had normal cilia. Some nonciliated cells were in clusters and had wrinkled corrugated surfaces. 20 days: Similar to 10 days. 10 days postexposure: Cilia nearly normal. Clusters of nonciliated cells were present and elevated above the surface. Clusters of nonciliated cells were interpreted as proliferative changes.	Mouse (Swiss Webster)	Ibrahim et al., 1980
1568	0.8	UV, NBKI	7 days, continuous with samples at 6, 24, 72 and 168 hr.	Exposure-related epithelial changes. TB cell populations changed after O_3 exposure; fewer ciliated and more non-ciliated secretory cells.	Rat	Lum et al., 1978
1568	0.8	UV, NBKI	4, 8, 12, 18, 26, 36, 50, and post 48 and 168 hr, continuous	Degeneration and necrosis of RB type 1 cells predominates from 4-12 hr. Type 1 cell most sensitive of RB epithelial cells. Labeling index highest at 50 hr. Mostly cuboidal bronchiolar cells but some type 2 cells. Bronchiolar epithelium hyperplastic after 50 hr exposure, which persisted following 7 days postexposure. Intraluminal macrophages increased during exposure, but marked clusters of K cells at 26-36 hr.	Monkey (Rhesus)	Castleman et al., 1980

ABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued)

Ozone concentration µg/m³	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]		Species	Reference
1568	0.8	UV, NBKI	3 days, continuous 0, 2, 6, 9, 16, and 30 days post-exposure; 2nd 3 days continuous after 6, 13, and 27 days postexposure	1st Exposure:	TB epithelium flattened and covered with debris. Ciliated cells either unrecognizable or had shortened cilia. The type of most epithelial cells could not be determined. Proximal alveoli had clumps of macrophages and cell debris. Type 2 cells lined surfaces of many proximal alveoli. Occasionally, denuded basal lamina or type 1 cell swelling.	Rat (Sprague-Dawley; 70 days old)	Plopper et al., 1978
				Postexposure: 6 days:	Most obvious lesions were not present. TB epithelium had usual pattern. Clumps of macrophages had cleared from the lumen. Most proximal alveoli lined by normal type 1 and 2 cells.		
				30 days:	Lungs indistinguishable from controls.		
				2nd 3-Day Exposure:	6 or 27 days after the end of the 1st. Lesions same as 1st exposure.		
1666	0.85 Similar exposure regimen for 14 ppm NO_2, but not mixtures.	ND	1, 2, 3 days, continuous	Birth to weaning at 20 days: "Very little indication of response" or "tissue nodules" with dissecting microscope.		Rat (Sprague-Dawley; 1, 5, 10, 15, 20, 25, 30, 35, and 40 days old)	Stephens et al., 1978
				12 days:	NO_2 lesions but no O_3 lesions.		
				22 days old:	O_3, loss of cilia, hypertrophy of TB cells, tendency towards flattening of luminal epithelial surface.		
				32 days old:	O_3, loss of cilia, and significant hypertrophy of TB epithelial cells.		
				21 days old and older:	Alveolar injury, including sloughing to type 1 cells resulting in bare basal lamina.		
				Response plateau is reached at 35 days of age.			
1960	1.0	NBKI	~60 weeks, ~5 days/week, 6 hr/day (268 exposures)	Chronic injury occurred in the lungs of each species of small animal. The principal site of injury was in the terminal airway, as manifested by chronic bronchiolitis and bronchiolar wall fibrosis resulting in tortuosity and stenosis of the passages.		Mouse, Hamster, Rat	Stokinger et al., 1957

TABLE 10-1. MORPHOLOGICAL EFFECTS OF OZONE (continued)

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
µg/m³	ppm					
1960 to 5880 1960 1960 1960 3920 5880	1.0 to 3.0 1.0 1.0 1.0 2.0 3.0	ND	18 months, 8-24 hr/day A = 8 hr/day B = 16 hr/day C = 24 hr/day D = 8 hr/day E = 8 hr/day	Result: A 1 ppm, 8 hr/day: Minimal fibrosis occasionally and randomly in the periphery of an alveolar duct. A few "extra" macrophages in central alveoli. B 1 ppm, 16 hr/day: Occasional fibrous strands in some alveolar openings of RBs and ADs. A few more "extra" macrophages. C 1 ppm, 24 hr/day: More extensive fibrosis of centriacinus. Thickened AD walls. More "extra" macrophages. Sporadic hyperplasia of epithelium of RB and AD. D & E More fibrosis. Epithelial hyperplasia and squamous metaplasia.	Dog	Freeman et al., 1973
1960 and 3920	1.0 and 2.0 Also mixtures with H_2SO_4	CHEM, NBKI	2 or 7 days, 6 hr/day	Results: O_3 alone: Lesions limited to centriacinus. 1 ppm: Hypertrophy and hyperplasia of TB epithelium. Centriacinar alveoli had increased type 2 cells, increased macrophages, and thickened walls. Some edema in all animals. Lesions less severe at 7 days than at 2 days. This adaptation was more rapid in rats than guinea pigs. 2 ppm: Same plus loss of cilia in bronchi. O_3 plus H_2SO_4 No additive or synergistic morphological changes.	Rat and Guinea pig	Cavender et al., 1977

[a] Measurement method: MAST = KI-coulometric (Mast meter); CHEM = gas phase chemiluminescence); NBKI = neutral buffered potassium iodide; UV = UV photometry; ND = not described.

[b] Calibration method: NBKI = neutral buffered potassium iodide.

[c] Abbreviations used: LM = light microscope; EM = electron microscope; SEM = scanning electron microscope; TEM = transmission electron microscope; PAM = pulmonary alveolar macrophage; RB = respiratory bronchiole; TB = terminal bronchiole; AD = alveolar duct; IAS = interalveolar septa; LDH = lactic dehydrogenase; SER = smooth endoplasmic reticulum. RER = rough endoplasmic reticulum.

and glands associated with the sense of smell. Significant morphological differences exist among the various animal species used for O_3 exposures as well as between most of them and man (Schrieder and Raabe, 1981; Gross et al., 1982). With the exception of the cervical trachea, these structures have received little attention with respect to O_3 sensitivity, but O_3 removal through "scrubbing" has been studied (Yokoyama and Frank, 1972; and Miller et al., 1979).

The lower or intrathoracic conducting airways include the thoracic trachea, bronchi, and bronchioles. Species variation of lower airway structure is large, as recorded at the NIH workshop on Comparative Biology of the Lung: Morphology (National Institutes of Health, 1983). The thoracic trachea and bronchi have epithelial and subepithelial tissues similar to those of the upper conducting airways. In bronchioles, the epithelium does not contain mucous (goblet) cells, but in their place are specialized nonciliated bronchiolar epithelial cells, which in some species can appropriately be called "Clara" cells. Subepithelial tissues are sparse and do not contain glands.

The sensitive cell of the upper and lower conducting airways is the ciliated cell, which is primarily responsible for physical clearance or removal of inhaled foreign material from conducting airways of the respiratory system (see Section 10.3.4). The effects of O_3 on this sensitive cell type, which is distributed throughout the length of conducting airways, are detected through various physiological tests and several types of morphological examination (Kenoyer et al., 1981; Oomichi and Kita, 1974; Phalen et al., 1980; Frager et al., 1979; Abraham et al., 1980).

The other portion of the respiratory system directly damaged by inhalation of O_3 is the junction of the conducting airways with the gaseous exchange area. The structure and cell makeup of this junction varies with the species. In man, the most distal conducting airways, the terminal bronchioles, are followed by several generations of transitional airways, the respiratory bronchioles, which have exchange areas as a part of their walls. In most of the species used for experimental exposures to O_3, (i.e., mouse, rat, guinea pig, and rabbit), the terminal bronchioles are followed by alveolar ducts rather than respiratory bronchioles. The only common experimental animals with respiratory bronchioles are the dog and monkey, and they have fewer generations of nonrespiratory bronchioles than does man as well as differences in the cells of the respiratory bronchioles (National Institutes of Health, 1983).

10.3.1.1.1 Airways

10.3.1.1.1.1 Upper airways (nasal cavity, pharynx, and larynx). The effects of O_3 on the upper extrathoracic airways have received little attention. The effect of upper airway scrubbing on the level of O_3 reaching the more distal conducting airways has been studied in rabbits and guinea pigs (Miller et al., 1979). They demonstrated removal of approximately 50 percent of ambient concentrations between 196 and 3920 $\mu g/m^3$ (0.1 and 2.0 ppm). Earlier, Yokoyama and Frank (1972) studied nasal uptake in dogs. They found uptake to vary with flow rate as well as with O_3 concentration. At 510 to 666 $\mu g/m^3$ (0.26 to 0.34 ppm) of O_3, the uptake at low flows of 3.5 to 6.5 L/min was 71.7 ± 1.7 percent, and at high flow rates of 35 to 45 L/min the uptake was 36.9 ± 2.7 percent. At 1529 to 1568 $\mu g/m^3$ (0.78 to 0.8 ppm), the uptakes at low and high flows were 59.2 ± 1.3 percent and 26.7 ± 2.1 percent, respectively. The scrubbing effect of the oral cavity was significantly less at all concentrations and flow rates studied. Species variations in uptake by the nasal cavity probably relate to species differences in the complexity and surface areas of the nasal conchae and meatuses (Schreider and Raabe, 1981).

No studies of the effects of O_3 on the nasal cavity were found, but two references to articles in the Japanese literature were cited by Ikematsu (1978). At least one study of the morphological effects of ambient levels of O_3 on the nasal cavity of nonhuman primates is in progress, but not published.

The effects of 392, 1960, and 9800 $\mu g/m^3$ (0.2, 1.0, and 5.0 ppm) of O_3 on the tonsils, the primary lymphoreticular structures of the upper airways, were studied. In palatine tonsils from rabbits exposed to 392 $\mu g/m^3$ (0.2 ppm) of O_3 continuously for 1 and 2 weeks, Ikematsu (1978) reported epithelial detachment and disarrangement and a slight cellular infiltration. The significance of these observations to the function of immune mechanisms in host defense is unknown.

10.3.1.1.1.2 Trachea. Tracheal epithelial lesions have been described in several species following exposure to less than 1960 $\mu g/m^3$ (1 ppm) of O_3. Boatman et al. (1974) exposed anesthetized, paralyzed cats to 510, 980, or 1960 $\mu g/m^3$ (0.26, 0.50, or 1 ppm) of O_3 via an endotracheal tube for 4.7 to 6.6 hr. This exposure technique bypassed the nasal cavity, resulting in higher tracheal concentrations than in usual exposures. They reported desquamation of ciliated epithelium at 1960 $\mu g/m^3$ (1 ppm) of O_3, but none at 510 or 980 $\mu g/m^3$ (0.26 or 0.5 ppm).

In rats exposed to 960 or 1568 μg/m^3 (0.5 or 0.8 ppm) of O_3, 8 or 24 hr/day for 7 days, Schwartz et al. (1976) described focal areas of the trachea in which the cilia were reduced in density and were of variable diameter and length. Mucous cells appeared to have been fixed in the process of discharging mucigen droplets. These changes were more easily seen with the scanning electron microscope (SEM) and were not obvious in rats exposed to 392 μg/m^3 (0.2 ppm) of O_3 for the same times. Cavender et al. (1977), when using only light microscopy (LM), studied tracheas from rats and guinea pigs exposed for 7 days to 1960 or 3920 μg/m^3 (1 or 2 ppm) of O_3 or sulfuric acid (H_2SO_4) or both. The article does not state the hours of exposure per day. Tracheal lesions, which consisted of reduced numbers of cilia and goblet cells, were reported only for guinea pigs exposed to O_3. Animals exposed to both pollutants had lesions similar to those exposed to O_3 alone.

By using SEM and transmission electron microscopy (TEM), Castleman et al. (1977) described shortened and less dense cilia in tracheas from bonnet monkeys exposed to 392 or 686 μg/m^3 (0.2 or 0.35 ppm), 8 hr/day for 7 days. Lesions occurred as random patches or longitudinal tracts. In these areas, the nonciliated cells appeared to be more numerous. The TEM study revealed that cells with long cilia had the most severe cytoplasmic changes, which included dilated endoplasmic reticulum, swollen mitochondria, and condensed nuclei, some of which were pyknotic. In lesion areas, evidence of ciliogenesis was seen in noncilated cells with a microvillar surface. Mucous cells did not appear to be significantly altered, but some had roughened apical surfaces. The changes were more variable and less severe in the 392 μg/m^3 (0.2 ppm) group. More extensive and severe lesions of similar nature were seen in tracheas from rhesus monkeys exposed to 980 or 1568 μg/m^3 (0.5 or 0.8 ppm) of O_3 in the same exposure regimen (Dungworth et al., 1975b; Mellick et al., 1977).

After mice were exposed to 1568 μg/m^3 (0.8 ppm) of O_3 24 hr/day for 6, 10, or 20 days and for 20 days followed by a 10-day postexposure period during which the animals breathed filtered air, the surface of the tracheas was examined by SEM by Ibrahim et al. (1980). Short and normal-length cilia were seen at 6 days, but at 10 and 20 days, a marked loss of cilia and few normal cilia were seen. Some of the nonciliated cells occurred as clusters and had wrinkled or corrugated surfaces. After the mice breathed filtered air for 10 days, the surface morphology of the cilia returned to near normal, but the clusters of nonciliated cells were still present. Earlier, Penha and Werthamer (1974) observed metaplasia of the tracheal epithelium from mice exposed to high concentrations of O_3 (4900 μg/m^3, 2.5 ppm) for 120 days. After the mice breathed clean air for 120 days, the metaplasia disappeared, and the epithelium had a nearly normal frequency of ciliated and nonciliated cells.

10.3.1.1.1.3 Bronchi. Bronchial lesions were studied in many of the same animals as those whose tracheal lesions are described above and were reported as generally similar to the tracheal lesions. At low concentrations (Castleman et al., 1977), lesions tended to be more severe in the trachea and proximal bronchi than in distal bronchi or in the next segment of the conduction airways, the nonalveolarized bronchioles. Eustis et al. (1981) reported lesions in lobar, segmental, and subsegmental bronchi from bonnet monkeys exposed to 980 or 1568 μg/m^3 (0.5 or 0.8 ppm) of O_3 8 hr/day for 7, 28, or 90 days. Lesions at 7 days were similar to those previously described by Mellick et al. (1977) and Castleman et al. (1977), as summarized above. At 28 and 90 days, lesions were not readily apparent by LM, but extensive damage to ciliated cells was seen using SEM. Uniform shortening and reduced density of cilia were seen in linear, parallel arrays. In these areas, the numbers of cells with a flat surface covered by microvilli increased. Sato et al. (1976a,b) studied bronchi from vitamin E-deficient and control rats exposed to 588 μg/m^3 (0.3 ppm) of O_3 3 hr/day for up to 16 days. Using LM, they did not see bronchial lesions with asymmetrical swelling and surface roughness, which were obvious with SEM. The observations of Sato et al. (1976a) support the concept that lesions in conducting airways are best seen with SEM and that LM tends to underestimate damage to these ciliated airways. In these short-term studies, lesions were more prominent in vitamin E-deficient rats. This is in contrast to later studies in which Sato et al. (1978, 1980) exposed vitamin E-deficient and supplemented rats to 588 μg/m^3 (0.3 ppm) of O_3 3 hr/day, 5 days/week for 7 months following which they did not see clear differences with SEM or TEM.

10.3.1.1.1.4 Bronchioles. There are two types of bronchioles with similar basic structure: those without alveoli in their walls (i.e., nonalveolarized) and those with alveoli opening directly into their lumen (respiratory bronchioles). Man and the larger experimental animals (e.g., nonhuman primates and dogs) have both nonrespiratory and respiratory bronchioles, whereas most of the smaller experimental animals (e.g., mice, rats, and guinea pigs) have only nonrespiratory bronchioles. Because the types, functions, and lesions of epithelial cells are different, these two types of bronchioles will be discussed separately.

Nonrespiratory bronchioles are conducting airways lined by two principal types of epithelial cells: the ciliated and nonciliated bronchiolar cells. The latter cell is frequently called the Clara cell. Although man and most animals have several generations of nonrespiratory bronchioles, some nonhuman primates have only one (Castleman et al., 1975). The last-generation conducting airway before the gas exchange area of the lung is the terminal bronchiole. Terminal bronchioles may end by forming respiratory bronchioles, as in man, monkeys, and dogs, or by forming alveolar ducts, as in mice, rats, and guinea pigs. The acinus, the functional unit of the lung, extends distally from the terminal bronchiole and includes the gas exchange area supplied by the terminal bronchiole and the vessels and nerves that service the terminal bronchiole and its exchange area.

A major lesion due to O_3 exposure occurs in the central portion of the acinus, the centriacinar region, which includes the end of the terminal bronchiole and the first few generations of either respiratory bronchioles or alveolar ducts, depending on the species. The centriacinar region is the junction of the conducting airways with the gas exchange tissues. The O_3 lesion involves both the distal portion of the airway and the immediately adjacent alveoli, the proximal alveoli. In animals with respiratory bronchioles, the lesion is a respiratory bronchiolitis. Regardless of species differences in structure, the lesion occurs at the junction of the conducting airways with the gas exchange area.

Terminal bronchiolar lesions in rats due to inhalation of $\leq$ 1960 μg/m^3 ($\leq$ 1.0 ppm) of O_3 for 2 hr to 1 week have been described by Stephens et al. (1974a), Evans et al. (1976a,c), Schwartz et al. (1976), and others (Table 10-1). Ciliated cells are the most sensitive of the airway cells, and fewer of them are found in the bronchiolar epithelium of exposed animals. Those ciliated cells present tend to have cilia with focal blebs and blunt ends. Damaged ciliated cells are replaced by nonciliated bronchiolar (Clara) cells (Evans et al., 1976a; Lum et al., 1978), which become hyperplastic. The typical projection of the nonciliated or Clara cell into the lumen is reduced, and the luminal surface has increased granularity. The reduction in projection height appears to be due to a reduction in agranular (smooth) endoplasmic reticulum (Schwartz et al., 1976). Many ciliated cells contain basal bodies and precursors of basal bodies indicative of ciliogenesis (Schwartz et al., 1976). The few brush cells present in nonrespiratory bronchioles appeared normal (Schwartz et al., 1976). The lesions were more severe in higher generation, more distal nonrespiratory bronchioles than in the lower generation, more proximal nonrespiratory bronchioles.

In an earlier study, Freeman et al. (1974) exposed month-old rats continuously to 1058 or 1725 $\mu g/m^3$ (0.54 or 0.88 ppm) of O_3 for 4 hr to 3 weeks. In addition to the centriacinar accumulations of macrophages and the hyperplasia of the distal airway epithelium, they reported an increase in connective tissue elements and collagen-like strands which formed bridges across alveolar openings. In the 1725-$\mu g/m^3$ (0.88-ppm) O_3 group, the fibrosis was pronounced and sometimes extended into terminal bronchioles. In the same study, Freeman et al. (1974) exposed month-old rats to a mixture of 1764 $\mu g/m^3$ (0.9 ppm) O_3 and one of 1690 $\mu g/m^3$ (0.9 ppm) nitrogen dioxide, or to a mixture of 490 $\mu g/m^3$ (0.25 ppm) O_3 and 4700 $\mu g/m^3$ (2.5 ppm) nitrogen dioxide. After 60 days of exposure to the 0.9/0.9 mixture, Freeman et al. (1974) reported that "both grossly and microscopically, the appearance of the lungs was characteristic of advanced experimental emphysema," referring to earlier nitrogen dioxide exposures (Freeman et al., 1972). Freeman et al. (1974) did not report emphysema in rats exposed to O_3 alone, only in those rats exposed to the 0.9/0.9 mixture. The topic of emphysema is discussed later (Section 10.3.1.4.2).

Results differ in three studies of long-term (3- to 6-month) exposures of rats to < 1960 $\mu g/m^3$ (<1.0 ppm) for 6 or 8 hr/day. The differences appear to be due at least in part to the methods used to evaluate the bronchioles. When using only LM to study effects in rats exposed for 6 months to 980 $\mu g/m^3$ (0.5 ppm) for 6 hr/day, Cavender et al. (1978) did not find exposure-related lesions. Using SEM and TEM to supplement the LM technique, Boorman et al. (1980) and Moore and Schwartz (1981) reported significant bronchiolar lesions following exposure to 980 or 1568 $\mu g/m^3$ (0.5 or 0.8 ppm) of O_3 8 hr/day for 90 or 180 days. In both studies, loss or shortening of cilia and flattening of the luminal projections of nonciliated bronchiolar cells were observed in terminal bronchioles at each time period, including the end of exposure at 90 or 180 days. Clusters of four to six nonciliated bronchiolar cells, in contrast to dispersed individual cells in controls, were seen at 90 days in both studies, but not at 180 days. However, in 2 of the 12 rats exposed 180 days, larger nodular aggregates of hyperplastic cells projected into the bronchial lumen.

After 50, 90, and 180 days of exposure, the nature of the junction between the terminal bronchiole and the alveolar ducts changed from the sharp demarcation seen in controls to a gradual transition with the appearance of a respiratory bronchiole. Both ciliated and nonciliated bronchiolar cells were seen on thickened tissue ridges between alveoli. This change could result from either alveolarization of the terminal bronchiole or bronchiolization of alveolar ducts. Although this change in the airway morphology persisted, the changed segment reduced in length after the 180-day-exposed rats had breathed filtered air for 62 postexposure days. The addition of H_2SO_4 to these concentrations of O_3 for the same exposure times did not potentiate the lesions seen in the O_3-alone rats (Moore and Schwartz, 1981; Cavender et al., 1978; Juhos et al., 1978).

Ozone-induced bronchiolar lesions in mice are similar to those seen in rats, but the hyperplasia of the nonciliated cells is more severe (Zitnik et al., 1978); Ibrahim et al., 1980). Following high concentrations (4900 $\mu g/m^3$, 2.5 ppm), Penha and Werthamer (1974) noted persistence (unchanged in frequency or appearance) or micronodular hyperplasia of noncilated bronchiolar cells for 120 postexposure days following 120 days of exposure. At lower O_3 levels (980 or 1568 $\mu g/m^3$, 0.5 or 0.8 ppm), the hyperplasia was pronounced (Zitnik et al., 1978; Ibrahim et al., 1980). Ibrahim et al. (1980) noted hyperplastic clusters of nonciliated cells 10 days after exposure but did not make observations after longer postexposure periods.

Guinea pigs were exposed by Cavender et al. (1977, 1978) continuously to 1 or 2 ppm of O_3 for 2 or 7 days in acute studies and to 980 $\mu g/m^3$ (0.5 ppm) 6 hr/day, 5 days/week for 6 months. Morphological effects were studied only by LM. The acute, higher- concentration distal-airway lesions were similar to those seen in rats and included loss of cilia and hyperplasia of nonciliated cells. The authors reported that the long-term, lower concentration lesions were more severe in guinea pigs than those in rats exposed to a similar regimen. The lesions were no more severe in guinea pigs exposed to a combination of H_2SO_4 aerosol and O_3.

10.3.1.1.2 Parenchyma. Ozone does not affect the parenchyma in a uniform manner. The centriacinar region (i.e., the junction of the conducting airways with the gas exchange area) is the focus of damage, and no changes have been reported in the peripheral portions of the acinus.

10.3.1.1.2.1 Respiratory bronchioles. Respiratory bronchioles are the focus of effects, because they are the junction of the conducting airways with the gas exchange area. However, not all animals have respiratory bronchioles. They are well developed in man but are absent or poorly developed in the common laboratory animals frequently used for O_3 study, with the exception of dogs (Freeman et al., 1973) and macaque monkeys (Mellick et al., 1975, 1977; Dungworth et al., 1975b; Castleman et al., 1977, 1980; Eustis et al., 1981). Short-term exposures of monkeys to 392, 686, 980, or 1568 $\mu g/m^3$ (0.2, 0.35, 0.5, or 0.8 ppm) of O_3 8 hr/day for 7 days resulted in damage to type 1 cells and hyperplasia of nonciliated bronchiolar cells, which were visible by either light or electron microscopy. At lower concentrations, these lesions were limited to the proximal, lower generation respiratory bronchioles. At higher concentrations, the lesions extended deeper into the acinus. The lesions were focused at the junction of the conducting airways with the gas exchange area and extended from that junction with increasing O_3 concentration.

The pathogenesis of the lesions due to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 for periods up to 50 hr of exposure was studied quantitatively by Castleman et al. (1980). Damage to type 1 cells was very severe following 4, 8, and 12 hr of exposure. Type 1 cell necrosis, which resulted in bare basal lamina, reached a maximum at 12 hr. The absolute and relative numbers of these cells decreased throughout the exposure. Only a few type 2 cells had mild degenerative changes and only at 4 or 12 hr of exposure. Cuboidal bronchiolar cells had mild degenerative changes, swollen mitochondria, and endoplasmic reticulum at all times except 18 hr. Both cuboidal bronchiolar and type 2 cells functioned as stem cells in renewal epithelium, and both contributed to the hyperplasia seen at the latter exposure times. The inflammatory exudate included both fibrin and a variety of leukocytes in the early phases. In the latter phases, the inflammatory cells were almost entirely macrophages. Inflammatory cells were also seen in the walls of respiratory bronchioles and alveoli opening into them. These lesions were not completely resolved after 7 days of filtered air breathing.

Monkeys exposed to 960 or 1568 $\mu g/m^3$ (0.5 or 0.8 ppm) of O_3 8 hr/day for 90 days had a low-grade respiratory bronchiolitis characterized by hypertrophy and hyperplasia of cuboidal bronchiolar cells and intraluminal accumulation of macrophages (Eustis et al., 1981). After the 90-day exposure, the percent of cuboidal respiratory bronchiolar epithelial cells was 90 percent rather than the 60 percent found in controls. Intraluminal cells, mostly macrophages, reached a maximum of a thirty-seven-fold increase after 7 days of exposure. Their numbers decreased with continued exposure, but at 90 days of exposure, they were still seven-fold those of controls. This study did not include a postexposure period.

In an earlier study, Freeman et al. (1973) exposed female beagle dogs to 1960 μg/m^3 (1 ppm) of O_3 8, 16, or 24 hr/day for 18 months. Dogs exposed to 1960 μg/m^3 (1 ppm) of O_3 for 8 hr/day had the mildest lesions, which were obvious only in the terminal airway and immediately adjacent alveoli, where minimal fibrosis and a few extra macrophages were seen. More fibrous strands and macrophages were seen in centriacinar areas of lungs from dogs exposed 16 hr/day. Lungs from dogs exposed 24 hr/day had terminal airways distorted by fibrosis and thickened by both fibrous tissue and a mononuclear cell infiltrate. Relatively broad bands of connective tissue were reported in distal airways and proximal alveoli. Epithelial hyperplasia was seen sporadically in the bronchiolar-ductal zone. Other dogs in that study exposed to 3920 or 5880 μg/m^3 (2 or 3 ppm) of O_3 8 hr/day for the same period had more severe fibrosis, greater accumulations of intraluminal macrophages, and areas of both squamous and mucous metaplasia of bronchiolar epithelia.

10.3.1.1.2.2 Alveolar ducts and alveoli. Alveoli in the centriacinar region, but not those at the periphery of the acinus, are damaged by ambient levels of O_3 (Stephens et al., 1974b; Schwartz et al., 1976; Mellick et al., 1977). The lesion is characterized by the destruction of type 1 alveolar epithelial cells exposing the basal lamina; an accumulation of inflammatory cells, especially macrophages; hyperplasia of type 2 alveolar epithelial cells that recover the denuded basal lamina; and thickening of the interalveolar septa. In animals with respiratory bronchioles (e.g., dog, monkey) the alveoli involved at low concentrations are those opening directly into the respiratory bronchiolar lumen of low-generation respiratory bronchioles (Dungworth et al., 1975b). As the concentration is increased, the lesions include alveoli attached to but not, seemingly, opening into the respiratory bronchioles and extending distally to higher-generation respiratory bronchioles (Mellick et al., 1977). In monkeys exposed to 1568 μg/m^3 (0.8 ppm) of O_3, alveoli opening into alveolar ducts are minimally involved (Mellick et al., 1977). In animals that lack respiratory bronchioles (e.g., rat, mouse, guinea pig) the alveoli involved open into or are immediately adjacent to the alveolar ducts formed by the termination of the terminal bronchiole.

Type 1 cell damage and loss have been reported in rats after a 2-hr exposure to 392 μg/m^3 (0.2 ppm) of O_3 (Stephens et al., 1974a). Recovering of denuded basal lamina by type 2 cells has been reported to start as early as 4 hr (Stephens et al., 1974b). The type 2 cell labeling index following tritiated thymidine reached a maximum at 2 days of continuous exposure to either 686 or 980 μg/m^3 (0.35 or 0.5 ppm) of O_3 (Evans et al., 1976b). Although the labeling index decreases as the exposure continues (Evans et al., 1976b), clusters of type 2 cells and cells intermediate between types 2 and 1 were reported following 90 days of exposure to 1568 μg/m^3 (0.8 ppm) by Boorman et al. (1980). They interpreted these intermediate cells as due to delay or arrest of the transformation from type 2 to type 1 epithelial cells. Type 1 cell damage and occasional sloughing were observed by Barry et al. (1983) in newborn rats exposed to 490 μg/m^3 (0.25 ppm) of O_3 12 hr/day for 6 weeks. By using LM and TEM morphometric techniques, these authors also found that centriacinar alveoli also had more type 1 and 2 epithelial cells and macrophages. The type 1 cells were smaller in volume, covered less surface, and were thicker. Sherwin et al. (1983) found increased numbers of lactate dehydrogenase (LDH)-positive cells, presumed to be type 2 alveolar epithelial cells, by automated LM morphometry of lungs from mice exposed to 588 μg/m^3 (0.3 ppm) of O_3 for 6 weeks. Moore and Schwartz (1981) reported nonciliated bronchiolar cells lined some alveoli opening into the transformed airways located between terminal bronchioles and alveolar ducts of rats exposed to 1568 μg/m^3 (0.8 ppm) of O_3 8 hr/day for 180 days. Sulfuric acid aerosol did not potentiate this lesion.

The inflammatory cell response appears to occur immediately following or concurrent with the type 1 cell damage and has been reported in monkeys as early as after 4 hr of 1568 μg/m^3 (0.8 ppm) of O_3 exposure (Castleman et al., 1980). In rats, the numbers of inflammatory cells per centriacinar alveolus appear to be related to O_3 concentration, at levels between 392 and 1568 μg/m^3 (0.2 and 0.8 ppm), during 7-day (Brummer et al., 1977) and 90-day exposures (Boorman et al., 1980). Using the same technique, Moore and Schwartz (1981) found statistically significant increases after 3, 50, 90, and 180 days of exposure 8 hr/day to 980 μg/m^3 (0.5 ppm) of O_3 and after 62 days of filtered air following 180 days of exposure. The addition of H_2SO_4 aerosol did not result in larger increases. In monkeys, the intensity of the response was greater than in rats exposed to the same O_3 concentration (1568 μg/m^3, 0.8 ppm) in the same regimen (8 hr/day) for 7, 28, or 90 days (Eustis et al., 1981). Although in both species the numbers of inflammatory cells per alveolus decreased with increasing length of exposure, the decrease was not as rapid in the monkey as in the rat (Eustis et al., 1981).

The interalveolar septa of centriacinar alveoli are thickened following exposure to ambient concentrations of O_3. After 7 days of continuous exposure, the thickening was attributed to eosinophilic hyaline material and mononuclear cells (Schwartz et al., 1976). Loose arrangements of cells and extracellular materials suggested separation by edema fluid. Castleman et al. (1980) also reported edema of interalveolar septa of monkeys exposed to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 for 4 to 50 hr. Boorman et al. (1980) used morphometric techniques on electron micrographs to quantitatively evaluate the thickness of centriacinar interaveolar septa. The arithmetic mean thickness was increased in rats exposed to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 8 hr/day for 20 or 90 days. The increased total thickness was due to thicker interstitium. Although several components could contribute to this increased thickness, the subjective impression was one of a mild interstitial fibrosis. This study is especially important, because it is quantitative and concerns rats exposed only 8 hr/day to 1568 $\mu g/m^3$ (0.8 ppm) of O_3.

Moore and Schwartz (1981), after exposing rats to 980 $\mu g/m^3$ (0.5 ppm) of O_3 24 hr/day for 180 days, reported very mild interstitial thickening of centriacinar interalveolar septa, which they concluded was due to collagen. Earlier, Freeman et al. (1973) morphologically demonstrated fibrosis in beagle dogs exposed to 1960 to 5880 $\mu g/m^3$ (1 to 3 ppm) of O_3 8 to 24 hr/day for 18 months.

In several biochemical studies, Last and colleagues have shown that O_3 is collagenic. In one of these (Last et al., 1979), the biochemical observations were correlated with histological observations of slides stained for collagen and reticulin. Elevated collagen synthesis rates were found at all concentrations and times studied. Mildly increased amounts of collagen were seen morphologically in centriacinar alveolar duct septa from most rats exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3 24 hr/day for 14 or 21 days. More severe lesions were seen in rats exposed to 1568 to 3920 $\mu g/m^3$ (0.8 to 2.0 ppm) of O_3 24 hr/day for 7, 14, or 21 days.

Only one published report addressed the biologically important question of the morphological effects that follow multiple sequential exposures to O_3 with several days of clean air interspersed between O_3 exposures (i.e., a multiple episode exposure regime). Plopper et al. (1978) exposed rats to 1568 $\mu g/m^3$ (0.8 ppm) O_3 continuously for 3 days, held them in the chambers breathing filtered air until postexposure day 6, 13, or 27, when they were again exposed to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 continuously for 3 days. Rats were also examined 2, 6, 9, 16, and 30 days after the first O_3 exposure. Lungs from rats breathing filtered air for 9 days after one 3-day exposure had only minimal lesions and after 30 days of filtered air were indistinguishable from controls. When the second 3-day O_3 exposure started 6 or 27 days after the end of the first exposure, the lesions appeared identical to each other and to those seen at the end of the first exposure.

10.3.1.1.3 Vasculature, blood, and lymphatics. Although edema is the apparent cause of death due to inhalation of high concentrations of O_3, there is very little morphological evidence of pulmonary vascular damage due to $\leq$ 1960 $\mu g/m^3$ ($\leq$ 1.0 ppm) of O_3 exposure. Bils (1970) reported capillary endothelial damage in mice less than 1 month of age exposed for 7 hr to 1960 $\mu g/m^3$ (1 ppm) of O_3, but this experiment has not been confirmed by others. Boatman et al. (1974) did demonstrate endothelial damage in cats exposed via an endotracheal tube to 510, 980, or 1960 $\mu g/m^3$ (0.26, 0.5, or 1.0 ppm) of O_3 for 4 to 6 hr, but it is not clear whether all exposure levels resulted in endothelial damage. In later studies that used pneumonectomized and control rabbits, Boatman et al. (1983) reported occasional swelling of capillary endothelium in both groups exposed to 784 $\mu g/m^3$ (0.4 ppm) of O_3 7 hr/day, 5 days/week for 6 weeks. Stephens et al. (1974b) reported occasional areas of endothelial swelling but concluded "the endothelium remains intact and rarely shows signs of significant injury." Stephens et al. (1974a) reported that "endothelium retained a relatively normal appearance" in rats exposed to 980 or 1764 $\mu g/m^3$ (0.5 or 0.9 ppm) of O_3 for 2 to 12 hr or 980 $\mu g/m^3$ (0.5 ppm) for up to 6 months. In rats exposed by the usual methods to 980 or 1568 $\mu g/m^3$ (0.5 or 0.8 ppm) of O_3 8 or 24 hr/day, centriacinar interalveolar septa had a loose arrangement of cells and extracellular material, indicating separation by edema fluid (Schwartz et al., 1976). These investigators did not find morphological evidence of damage to endothelial cells. Evidence of intramural edema in centriacinar areas was found by Castleman et al. (1980) in monkeys exposed to 1568 $\mu g/m^3$ (0.8 ppm) for 4 to 50 hr, but they did not report morphological evidence of vascular endothelial damage.

The earlier report of arterial lesions in rabbits exposed to 784 μg/m^3 (0.4 ppm) of O_3 6 hr/day, 5 days/week for 10 months by P'an et al. (1972) has not been confirmed by other investigators, because no other long-term exposure of rabbits has been reported. Possibly, susceptibility to arterial lesions was specific to this animal species, or these rabbits may have had intercurrent infectious disease which was more severe in exposed animals. The LM description indicates "some degree of inflammatory infiltrate" in all lungs, and in one exposed rabbit the lesions were so severe that "visualization of the mural framework of the alveoli was difficult."

No references to morphological damage of lymphatic vessels were found. This is not surprising, because following nasal inhalation of $\leq$ 1960 μg/m^3 ($\leq$1 ppm) of O_3, blood capillary endothelial damage has not been reported, and edema has been reported only in centriacinar structures. In the more generalized edema that follows exposure to higher concentrations, Scheel et al. (1959) reported perivascular lymphatics were greatly distended.

10.3.1.2 Sequence in which Sites are Affected as a Function of Concentration and Duration of Exposure. The sequence in which anatomic sites are affected appears to be a function of concentration rather than of exposure duration. At sites that are involved by a specific concentration, however, the stages in pathogenesis of the lesion relate to the duration of exposure. Multiple anatomical sites in the conducting and exchange areas of the respiratory system have been studied at sequential time periods in only a few studies. Stephens et al. (1974a) found minimal type 1 alveolar epithelial cell damage after a 2-hr exposure to 392 μg/m^3 (0.2 ppm) of O_3 and more significant damage 2 hr after exposure to 980 μg/m^3 (0.5 ppm) of O_3. Boatman et al. (1974) found lesions in both the conducting airways and parenchyma of cats exposed to 510, 980, or 1960 μg/m^3 (0.26, 0.5, or 1.0 ppm) via an endotracheal tube for times as short as 4.7 and 6.6 hr. Thus, if there is a time sequence in effect at various sites, it is a short time.

Increasing concentration not only results in more severe lesions, but also appears to extend the lesions to higher generations of the same type of respiratory structure (i.e., deeper into the lung) (Dungworth et al., 1975b). Several investigators who have described gradients of lesions have related them to assumed decreases in concentration of O_3 as it progresses through increasing generations of airways and to differences in protection and sensitivity of cells at various anatomic sites. For the conducting airways, Mellick et al. (1977) reported more severe and extensive lesions in the trachea and major bronchi than in small bronchi or terminal bronchioles of rhesus monkeys exposed to 980 or 1568 μg/m^3 (0.5 or 0.8 ppm) of O_3 8 hr/day for 7 days. For the acinus, they noted the most severe damage in proximal respiratory bronchioles and their alveoli rather than in more distal, higher generation ones. Proximal portions of alveolar ducts were only minimally involved. The predominant lesion was at the junction of the conducting airways with the exchange area. In monkeys, as in man, the proximal respiratory bronchioles, not alveolar ducts, are in the central portion of the acinus. Similar gradients of effects in the conducting airways and the centriacinar region were reported by Castleman et al. (1977), who studied bonnet monkeys exposed to 392 and 686 μg/m^3 (0.2 and 0.35 ppm) of O_3 8 hr/day for 7 days. In the centriacinar region, this gradient is most easily demonstrated by the hyperplasia of cuboidal cells in respiratory bronchioles that extended further distally in monkeys exposed to 686 rather than 392 μg/m^3 (0.35 than 0.2 ppm) of O_3.

The effects of duration of exposure are more complex. In the time frame of a few hours, an early damage phase has been observed at 2 or 4 hr of exposure (Stephens et al., 1974a,b; Castleman et al., 1980). Repair of the damage, as indicated by DNA synthesis by repair cells, occurs as early as 18 hr (Castleman et al., 1980) or 24 hr (Evans et al., 1976b; Lum et al., 1978). Stephens et al. (1974a) reported little change in the extent of damage after 8 to 10 hr of exposure. Full morphological development of the lesion occurs at about 3 days of continuous exposure (Castleman et al., 1980). Damage continues while repair is in progress, but at a lower rate. This phenomenon has been termed adaptation (Dungworth et al., 1975b). When the time frame is shifted from hours to days, severity of the lesion at 7 days differs little between exposures of 8 hr/day and 24 hr/day (Schwartz et al., 1976). When the time frame is again shifted from days to months of daily exposures, the centriacinar lesions diminish in magnitude, but a significant lesion remains (Boorman et al., 1980; Moore and Schwartz 1981; Eustis et al., 1981).

10.3.1.3. Structural Elements Affected

10.3.1.3.1 Relative sensitivity of cell types. The ciliated cell of airways and the type 1 (squamous) alveolar epithelial cell are the cells most sensitive to the effect of inhaled O_3 (Stephens et al., 1974a,b; Schwartz et al., 1976; Mellick et al., 1977; Castleman et al., 1980; Eustis et al., 1981). The amount of damage to these sensitive cells varies with their position in the respiratory system. As mentioned earlier, ciliated cells of the trachea and proximal, lower generation bronchi are subject to more damage than those located in distal, higher generation bronchi or in lower generation bronchioles proximal to the terminal bronchiole (Schwartz et al., 1976; Mellick et al., 1977). Ciliated cells in terminal bronchioles of animals without respiratory bronchioles (i.e., rats) are severely damaged by even low concentrations of O_3 (Stephens et al., 1974a; Schwartz et al., 1976), whereas those in terminal bronchioles of animals with respiratory bronchioles (i.e., monkeys) are much less subject to damage (Castleman et al., 1977; Mellick et al., 1977).

In a similar manner, type 1 alveolar epithelial cells located in the centriacinar region are subject to damage by low concentrations of O_3, but those in the peripheral portions of the acinus appear undamaged by the same or higher concentrations (Stephens et al., 1974a,b; Schwartz et al., 1976; Castleman et al., 1980).

Although type 2 alveolar epithelial cells are relatively resistant to O_3, some in centriacinar locations develop mild lesions detectable with the TEM (Castleman et al., 1980). Type 2 cells are progenitor cells that recover basal lamina denuded by necrosis or sloughing of type 1 cells and transform (differentiate) into type 1 cells when repairing the centriacinar O_3 lesion (Evans et al., 1976b).

Although nonciliated cuboidal bronchiolar cells are more resistant to O_3 than ciliated cells and are the progenitor cells for replacement of damaged ciliated cells (Evans et al., 1976a,c; Lum et al., 1978), they are a sensitive indicator of O_3 damage (Schwartz et al., 1976). Following exposure to 1960 $\mu g/m^3$ (< 1 ppm) of O_3, their height is reduced and their luminal surface is more granular (Schwartz et al., 1976). The reduction in height appears to be due to a loss of smooth endoplasmic reticulum (Schwartz et al., 1976).

Several investigators report that type 3 alveolar epithelial cells, the brush cells, are not damaged by less than 1 ppm of O_3 (Stephens et al., 1974a; Schwartz et al., 1976). No reports are available of damage to type 3 cells by higher concentrations.

Vascular endothelial cells in capillaries of the interalveolar septa may be much less sensitive than earlier reports indicated, because lesions are not described in detailed studies using TEM (Stephens et al., 1974a,b; Schwartz et al., 1976; Mellick et al., 1977). In the earlier reports, damaged endothelial cells were those located immediately deep to denuded basal lamina and resulted from sloughing of type 1 epithelial cells in the centriacinar region (Bils, 1970; Boatman et al., 1974). Stephens et al. (1974b) reported occasional areas of endothelial swelling but the endothelium in these areas appeared relatively normal and the capillary bed was intact (Stephens et al., 1974a,b).

Morphological damage to the various types of interstitial cells in the interalveolar septa has not been reported. During O_3 exposure, inflammatory cells migrate into the centriacinar interalveolar septa (Schwartz et al., 1976). Later, more collagen and connective tissue ground substance is found in the interalveolar septa (Moore and Schwartz, 1981). Only one morphometric evaluation of the centriacinar interalveolar septa is in the open literature (Boorman et al., 1980), and it does not provide detail concerning specific cell types and extracellular materials.

Mucous-secreting cells in conducting airways appear relatively resistant to O_3. Boatman et al. (1974), in studies of cats exposed to $\leq$ 1960 $\mu g/m^3$ ($\leq$ 1.0 ppm) of O_3 via an endotracheal tube for short periods, did find limited desquamation of these cells, but the authors also observed that most appeared intact and increased in size. Castleman et al. (1977) noted roughened apical surfaces of mucous cells, which appeared to be associated with mucigen droplets near the cell surface, but did not find other alterations in pulmonary mucous cells from monkeys exposed to 392 or 686 $\mu g/m^3$ (0.2 or 0.35 ppm) of O_3 8 hr/day for 7 days. Mellick et al. (1977) mention that mitochondrial swelling and residual bodies seen in ciliated cells were not seen in mucous cells in conducting airways of monkeys exposed to 980 or 1568 $\mu g/m^3$ (0.5 or 0.8 ppm) of O_3 8 hr/day for 7 days. Schwartz et al. (1976), who reported mucigen droplets being released from the apical surfaces of mucous cells and mucous droplets trapped among cilia, did not find changes suggesting damage to organelles in rats exposed to 392, 980, or 1568 $\mu g/m^3$ (0.2, 0.5, or 0.8 ppm) of O_3 8 or 24 hr/day for 7 days. No reports of damage to conducting airways other than to ciliated and mucous cells were found.

10.3.1.3.2 Extracellular elements (structural proteins). Although physiologic and biochemical changes following O_3 exposure suggest changes in the extracellular structural elements of the lung, no direct morphological evidence has been given of changes in the extracellular structural elements themselves, in contrast to changes in their location or quantity. These physiologic and biochemical studies are discussed elsewhere in this document. Three studies provide morphological evidence of mild fibrosis (i.e., local increase of collagen) in centriacinar interalveolar septa following prolonged exposure to $< 1960\ \mu g/m^3$ (< 1 ppm) of O_3 (Last et al., 1979; Boorman et al., 1980; Moore and Schwartz, 1981). Changes in collagen location or amounts, or both, which occur with the remodeling of the distal airways, were reported in two of those studies (Boorman et al., 1980; Moore and Schwartz, 1981). Additional evidence of more collagen or changes in collagen location is in the report of dogs exposed to 1960 or 5880 $\mu g/m^3$ (1 or 3 ppm) of O_3 for 18 months (Freeman et al., 1973).

10.3.1.3.3 Edema. Morphologically demonstrable alveolar edema, or alveolar flooding--an effect of higher-than-ambient levels of O_3 (Scheel et al., 1959; Cavender et al., 1977)--is not reported after exposures to $\leq 1960\ \mu g/m^3$ (≤ 1.0 ppm) of O_3 for short or long exposure periods (Schwartz et al., 1976; Cavender et al., 1978; Mellick et al., 1977; Eustis et al., 1981; Boorman et al., 1980; Moore and Schwartz, 1981). Mild interstitial edema of conducting airways (Mellick et al., 1977) and centriacinar parenchymal structures (Schwartz et al., 1976; Castleman et al., 1980; Mellick et al., 1977) is seen following exposure of monkeys or rats to $\leq 1960\ \mu g/m^3$ (≤ 1 ppm) of O_3 for several hours to 1 week. Interstitial edema is not reported following longer-term (i.e., weeks to months) exposure to $\leq 1960\ \mu g/m^3$ (≤ 1 ppm) or less (Cavender et al., 1977; Eustis et al., 1981; Boorman et al., 1980; Moore and Schwartz, 1981; Zitnik et al., 1978). Biochemical indicators of edema are described in Section 10.3.3.

10.3.1.4 Considerations of Degree of Susceptibility to Morphological Changes

10.3.1.4.1 Compromised experimental animals. Compromised experimental animals (e.g., those with a special nutritional or immunological condition) in a disease state or of young or old age may respond to O_3 exposure with greater, lesser, or a different type of response than the normal, healthy, young adult animals usually studied. Some of these may represent "at risk" human populations.

10.3.1.4.1.1 Vitamin E deficiency. Rats maintained on vitamin E-deficient diets tended to develop more morphological lesions following exposure to low levels of O_3 than did rats on the usual rations (Plopper et al., 1979; Chow et al., 1981). Rats maintained on a basal vitamin E diet equivalent to the average U. S. human adult intake were exposed to 196 or 392 $\mu g/m^3$ (0.1 or 0.2 ppm) of O_3 24 hr/day for 7 days. According to LM studies, two of the six rats on the basal vitamin E had increased numbers of macrophages in their centriacinar alveoli, a typical response to higher levels of O_3 (Schwartz et al., 1976). Of five rats on the usual rat chow diet exposed to 196 μg/m^3 (0.1 ppm) O_3 for the same period, LM revealed no increased centriacinar macrophages. LM analysis showed neither dietary group had lesions in the ciliated terminal bronchiolar epithelium. Rats in which lesions were observed by LM had increased macrophages, according to SEM analysis. Analysis by TEM showed that all rats exposed to 196 μg/m^3 (0.1 ppm) of O_3 differed from controls in that some of the centriacinar type 1 alveolar epithelial cells contained inclusions and were thicker.

Chow et al. (1981) fed month-old rats a basal vitamin E-deficient diet or that diet supplemented with 11 or 110 ppm vitamin E for 38 days, after which they were exposed either to filtered air or to 196 μg/m^3 (0.1 ppm) of O_3 continuously for 7 days. The morphology of six rats from each diet and exposure group was studied using SEM. None of the filtered-air control animals had lesions. Of the rats exposed to O_3, five of the six on the vitamin E-deficient diet, four of six on the deficient diet supplemented by 11 ppm vitamin E, and one of the six on the deficient diet supplemented by 110 ppm vitamin E developed the typical O_3 lesion as seen with SEM (Schwartz et al., 1976).

Sato et al. (1976a,b, 1978, 1980) exposed vitamin E-deficient and supplemented rats to 588 μg/m^3 (0.3 ppm) of O_3 3 hr daily for 16 consecutive days or 5 days a week for 7 months. The short-term experiments (Sato et al., 1976a,b) were marred by the presence of chronic respiratory disease in the rats, which may explain the investigators' finding of large amounts of debris and numerous small bodies "so thick that the original surface could not be seen" and their failure to find the typical centriacinar O_3 lesions reported by others (Stephens et al., 1974a; Schwartz et al., 1976). In the latter experiments, Sato et al. (1978, 1980) did not find morphological differences between the vitamin E-depleted and supplemented, filtered-air control rats or between vitamin E-depleted and supplemented, O_3-exposed rats. They did find mild centriacinar O_3 lesions in exposed rats from both vitamin E-deficient and supplemented groups.

Stephens et al. (1983) reported results of exposure of vitamin E-depleted and control young and old rats to 1764 μg/m^3 (0.9 ppm) of O_3 for 1, 3, 6, 12, 34, 48, and 72 hr. Vitamin E depletion was evaluated by determination of lung tissue levels. Lung response to ozone was based on characteristic tissue nodules previously reported by these authors when using a dissecting microscope rather than on conventional LM, SEM, or TEM. They concluded that response to injury and repair of the lung was independent of the level of vitamin E in lung tissue. Most of these studies included concurrent biochemical evaluations of oxidant metabolism and are discussed in Section 10.3.3.

10.3.1.4.1.2 Age at start of exposure. Although most exposures use young adult experimental animals, there are a few reports of exposures of very young animals (i.e., either before weaning or very soon thereafter).

Bartlett et al. (1974) exposed 3- to 4-week-old rats to 392 $\mu g/m^3$ (0.2 ppm) of O_3 for 30 days. Lung volumes, but not body weights, were significantly greater in the exposed rats. Light microscopy of paraffin sections of conventionally fixed lungs did not reveal differences between exposed and control rats in the lung parenchyma or terminal bronchioles, with the exception of two control animals which had lesions of "typical murine pneumonia." Morphometry was done on thick sections cut by hand with a razor blade from the dorsal and lateral surfaces of air-dried lungs rather than on the paraffin sections of conventionally fixed lungs. Morphometry using these nonrandom samples revealed significantly increased mean alveolar chord lengths and alveolar surface area, but no difference in alveolar numbers.

Freeman et al. (1974) exposed month-old rats to 1058 or 1725 $\mu g/m^3$ (0.54 or 0.88 ppm) of O_3 for periods of from 4 hr to 3 weeks. In addition to the centriacinar accumulations of macrophages and hyperplasia of distal airway epithelium seen by others following exposures of young adult animals, they reported an increase in connective tissue elements and collagen-like strands that formed bridges across alveolar openings. Fibrosis was pronounced in the 1725 $\mu g/m^3$ (0.88 ppm) group and sometimes extended into terminal bronchioles. Although fixed lung volumes were not done, the 1725-$\mu g/m^3$ (0.88 ppm) group required greater volumes of fixing fluid, evidence of larger lung volumes. In the same research report, Freeman et al. (1974) studied month-old rats exposed to 1764 $\mu g/m^3$ (0.9 ppm) of O_3 and 1690 $\mu g/m^3$ (0.9 ppm) nitrogen dioxide combined. After 60 days of exposure, they observed the gross and microscopic appearance of advanced experimental emphysema of the type they earlier described following nitrogen dioxide exposure (Freeman et al., 1972). Although others have reported larger fixed lung volumes in exposed young adult rats (Moore and Schwartz 1981), reports of emphysema following O_3 exposures are uncommon and are discussed in the next subsection of this document.

Stephens et al. (1978) exposed rats at 1, 5, 10, 20, 25, 30, 35, and 40 days of age to 1666 $\mu g/m^3$ (0.85 ppm) of O_3 continuously for 24, 48, or 72 hr. Rats exposed to O_3 before weaning at 20 days of age developed little or no evidence of injury, as evaluated by light and electron microscopy. Following weaning at 20 days of age, centriacinar lesions increased progressively, plateaued at 35 days of age, and continued until approximately 1 year of age.

Barry et al. (1983) exposed 1-day-old male rats and their mother to 490 $\mu g/m^3$ (0.25 ppm) of O_3 12 hr/day for 6 weeks. They observed persistence of the centriacinar damage to type 1 epithelial cells and increased centriacinar macrophages. By using LM and TEM morphometry of centriacinar regions, they reported an increase in both type 1 and 2 alveolar epithelial cells. The type 1 cells were smaller in volume, covered less surface, and were thicker. The authors were aware of the above study by Stephens et al. (1978) and discussed the possibility that much of the damage they observed may have occurred in the last 3 weeks of exposure (i.e., after weaning). Changes in lung function evaluated by Raub et al. (1983) are discussed in Section 10.3.2.

Bils (1970) studied the effects of 1176 to 2548 $\mu g/m^3$ (0.6 to 1.3 ppm) of O_3 on mice 4 days old and 1 and 2 months old. From his study, Bils concluded that the endothelium appeared to be the main target of the O_3, a conclusion not supported by more recent studies, which deal mostly with other species. Bils did note the lesions were more severe in the 4-day-old mice than in the 1- or 2-month-old mice.

10.3.1.4.1.3 Effect of pneumonectomy. Two to four weeks following pneumonectomy of rabbits, the contralateral lung increases in volume, weight, collagen, and protein content to approximate that of both lungs from controls, but alveolar multiplication appears dependent on age at surgery. Boatman et al. (1983) exposed pneumonectomized and control rabbits to 784 $\mu g/m^3$ (0.4 ppm) of O_3 7 hr/day, 5 days/week for 6 weeks. They examined the lungs with standard LM and TEM morphometric techniques, but not methods for alveolar numbers. Boatman and co-workers concluded that the lung growth that follows pneumonectomy occurred after O_3 exposure and that no difference existed between males and females in this response.

10.3.1.4.2 Emphysema following ozone exposure. The previous criteria document for O_3 (U.S. Environmental Protection Agency, 1978) cites three published research reports in which emphysema was observed in experimental animals following exposure to ≤ 1960 μg/m^3 (≤ 1 ppm) of O_3 for prolonged periods (P'an et al., 1972; Freeman et al., 1974; Stephens et al., 1976). Since then, no similar exposures (i.e., same species, O_3 concentrations, and times) have been documented to confirm these observations. An additional consideration is the similarity of the centriacinar lesion following O_3 exposure to that seen in young cigarette smokers (Niewoehner et al., 1974; Schwartz et al., 1976; Cosio et al., 1980; Wright et al., 1983) and the relationship between cigarette smoking and emphysema in humans (U.S. Department of Health, Education, and Welfare, 1967, 1969). Further, animals exposed to 1960 μg/m^3 (1 ppm) of O_3 reportedly have more voluminous lungs than controls (Bartlett et al., 1974; Moore and Schwartz, 1981). Thus, a restudy of these three reports in the 1978 document appears appropriate.

Stokinger et al. (1957) reported emphysematous changes in lungs from guinea pigs, rats and hamsters, but not mice or dogs, exposed 6 hr/day, 5 days/week for 14.5 months to a mean concentration of slightly more than 1960 μg/m^3 (1 ppm) of O_3. With the exception of the dogs, mortality rates were high in both control and exposed animals, ranging in the controls from 25 to 78 percent and in exposed from 11 to 71 percent. The published report indicates that emphysema was present but does not further characterize it as to the presence of only enlarged air spaces (CIBA, 1959) or enlarged air spaces accompanied by destructive changes in alveolar walls (World Health Organization, 1961; American Thoracic Society, 1962). The lungs were fixed via the trachea, making them suitable for studies of experimentally induced emphysema (American Thoracic Society, 1962). Stokinger et al. (1957) attributed the emphysema in the guinea pigs to the observed bronchial stenosis. Also in the guinea pigs were foci of "extensive linear fibrosis...considered to be caused by organization of pneumonic areas". In the rats, the mild degree of emphysema in those exposed "did not exceed the emphysema found in the unexposed control rats." In the hamsters, "mild to moderate" emphysema was present in exposed animals, but not controls. Emphysema is not mentioned in the figure legends, but three of them mention "alveoli are overdistended...alveolar spaces are dilated... dilation of alveolar ducts and air sacs." Evidence of destruction of alveolar walls is not mentioned. Later, however, Gross et al. (1965), in an unrefereed publication abstracted from a presentation at the seventh Aspen Conference on Research in Emphysema, reviewed the lesions in the hamsters from this exposure and described a "destructive process" that resulted in contraction of interalveolar septa not associated with enlargement of air spaces.

The earlier O_3 criteria document (U.S. Environmental Protection Agency, 1978) cites Stephens et al. (1976), a "long abstract" that appears not to be refereed. This brief article states "rats exposed continuously for long periods (3 - 5 months) to 28,200 µg/m^3 (15.0 ppm) NO_2 or 1568 µg/m^3 (0.8 ppm) O_3 develop a disease that closely resembles emphysema" but does not provide additional evidence other than citing five earlier studies by the Stanford group of investigators. Each of those five references was checked for studies of animals exposed to O_3. Three articles describe only NO_2-exposed animals. The fourth reference (Freeman et al., 1973) is to an exposure of dogs to 1960 to 5880 µg/m^3 (1 to 3 ppm) of O_3 8 to 24 hr daily for 18 months and was cited earlier in this document. Emphysema is not mentioned in that article. Neither is emphysema mentioned in the fifth reference (Stephens et al., 1974b), which was also cited earlier in this document. These investigators did describe (Freeman et al., 1974) a group of month-old rats exposed continuously for 3 weeks to 1725 µg/m^3 (0.88 ppm) of O_3, half of which died and had "grossly inflated, dry lungs." In this same study, they also exposed month-old rats to a mixture of 1690 µg/m^3 (0.9 ppm) of NO_2 and O_3 continuously for 60 days, at which time the lungs were grossly enlarged, and "both grossly and microscopically, the appearance of the lungs was characteristic of advanced experimental emphysema" of the type they earlier reported followed NO_2 alone at much higher concentrations (Freeman et al., 1972).

The third citation in the O_3 criteria document (U.S. Environmental Protection Agency, 1978) is to P'an et al. (1972). These investigators exposed rabbits to 784 µg/m^3 (0.4 ppm) of O_3 6 hr/day, 5 days/week for 10 months. Tissues were apparently fixed by immersion rather than infusion via the trachea, which is not in accord with the American Thoracic Society's diagnostic standard for emphysema and makes emphysema lesions much more difficult to accurately evaluate. The lesions related to emphysema are only very briefly described and illustrated in only one figure. The authors also report that "all lungs showed some degree of inflammatory infiltrate" and "lungs of the sixth were so congested that visualization of the mural framework of the alveoli was difficult." This is more reaction than reported in other species exposed to this comparatively low O_3 concentration. The rabbits were not specified pathogen free nor was the possibility considered that some lesions could be due to infectious agents. Neither did these investigators consider the possibility of spontaneous "emphysema and associated inflammatory changes" which Strawbridge (1960) described in lungs from 155 rabbits of various ages and breeds.

10.3.2 Pulmonary Function Effects

10.3.2.1 Short-Term Exposure. Results of short-term O_3 exposures of experimental animals are shown in Table 10-2. These studies were designed to evaluate the acute changes in lung function associated with O_3 exposure in a variety of species (mice, rats, guinea pigs, sheep, rabbits, cats, monkeys, and dogs) when compared to filtered-air exposure.

The effects of short-term local O_3 exposure of the lung periphery have been examined in dogs by Gertner et al. (1983a,b). A fiber-optic bronchoscope with an outside diameter of 5.5 mm was wedged into a segmental airway and a continuous flow of 196 or 1960 $\mu g/m^3$ (0.1 or 1.0 ppm) of O_3 was flushed through this airway and allowed to escape through the system of collateral channels normally present in the lung periphery. During exposure to either 196 or 1960 $\mu g/m^3$ (0.1 or 1.0 ppm) of O_3, airflow resistance through the collateral channels increased during the first 2 min of exposure. Resistance of the collateral channels continued to increase throughout exposure to 1960 $\mu g/m^3$ (1.0 ppm) of O_3, but decreased again to control levels during continued exposure to 196 $\mu g/m^3$ (0.1 ppm) of O_3. Based on these observations, the authors reported that tolerance appears to develop in the collateral airways to locally delivered O_3 at concentrations of 196 but not 1960 $\mu g/m^3$ (0.1 but not 1.0 ppm) of O_3.

Amdur et al. (1978) measured breathing pattern (tidal volume, respiration rate, and minute volume), pulmonary resistance, and dynamic pulmonary compliance in guinea pigs during 2-hr exposures to 431, 804, or 1568 $\mu g/m^3$ (0.22, 0.41, or 0.8 ppm) of O_3. Accelerated respiration rates with no significant changes in tidal volume were measured during exposures to all O_3 concentrations. The onset and magnitude of these changes in respiration rate were concentration dependent, and values of respiration rate remained elevated during a 30-min recovery period following exposure. Pulmonary compliance was significantly lower than pre-exposure values following 1 and 2 hr of exposure to 804 or 1568 $\mu g/m^3$ (0.41 or 0.8 ppm) of O_3, and values of compliance remained low during the 30-min recovery period. Changes in dynamic compliance were essentially the same during exposure to either 804 or 1568 $\mu g/m^3$ (0.41 or 0.8 ppm) of O_3. These investigators observed no significant change in pulmonary resistance during exposure to O_3. If anything, resistance tended to decrease throughout the exposure and recovery period.

TABLE 10-2. EFFECTS OF OZONE ON PULMONARY FUNCTION: SHORT-TERM EXPOSURES

Ozone concentration $\mu g/m^3$	Ozone concentration ppm	Measurement[a,b] method	Exposure duration & protocol	Observed effects[c]	Species	Reference
196 1960	0.1 1.0	MAST	30 min	Collateral system resistance increased rapidly during exposure, falling to control levels at 0.1 ppm but continuing to increase at 1.0 ppm of O_3.	Dog	Gertner et al., 1983a,b
431 804 1568	0.22 0.41 0.80	CHEM, NBKI	2 hr	Concentration-dependent increase in f_B for all exposure levels. No change in R_L, TV, or MV. Decreased $C_L$dyn during exposure to 0.4 and 0.8 ppm of O_3.	Guinea pig (200-300 g)	Amdur et al., 1978
470 to 2156	0.24 to 1.1	NBKI	12 hr	Premature airway closure at 6 hr, and 1 and 3 days following exposure, reflected by increased RV, CC, and CV (6 hr and 1 day only). Maximum effect 1 day following exposure, all values returned to normal by 7 days. Distribution of ventilation less uniform 6 hr following exposure. Increased lung distensibility in the mid-range of lung volumes (25-75% TLC) 7 days following exposure.	Rabbit	Inoue et al., 1979
510 980 1960	0.26 0.5 1.0	MAST	2.0 to 6.5 hr	Concentration-dependent increase in R_L during exposure. Decreased C_L and D_LCO but less frequent and less marked than changes in R_L. No change in VC or deflation pressure-volume curves.	Cat	Watanabe et al., 1973
666 1333 2117 2646	0.34 0.68 1.08 1.35	NBKI	2 hr	Increased f_B and decreased TV during exposure to all O_3 concentrations. Increased R_{rs} during exposure to 1.08 and 1.35 ppm of O_3.	Guinea pig (300-400 g)	Murphy et al., 1964
980	0.5	NBKI	2 hr	Slight increase in f_B and R_{rs} (to 113% of control values) during exposure.	Guinea pig (280-540 g)	Yokoyama, 1969

TABLE 10-2. EFFECTS OF OZONE ON PULMONARY FUNCTION: SHORT-TERM EXPOSURES (continued)

Ozone concentration		Measurement[a,b] method	Exposure duration & protocol	Observed effects[c]	Species	Reference
$\mu g/m^3$	ppm					
1470 1960 3920	0.75 1.0 2.0	CHEM	Continuous 1, 3, 7 or 14 days	The validity of this study is questioned because of low airflow through the exposure chambers and high mortality of exposed animals (66% mortality in rats exposed to 1 ppm of O_3).	Rat	Pepelko et al., 1980
1960	1	NBKI	3 hr	Reduced TLC at air inflation pressure of 30 cm H_2O, 1 to 3 days postexposure but not at 7 days. No difference in lung pressure-volume characteristics during lung inflation with saline.	Rabbit	Yokoyama, 1972, 1973
1960	1	NBKI	6 hr/day, 7 to 8 days	Increased R_L and decreased $C_L dyn$ 1 day following exposure. No change in MEFV curves.	Rabbit	Yokoyama, 1974

[a] Measurement method: MAST = KI-coulometric (Mast meter); CHEM = gas phase chemiluminescence; NBKI = neutral buffered potassium iodide.

[b] Calibration method: NBKI = neutral buffered potassium iodide.

[c] See Glossary for the definition of pulmonary symbols.

The lack of a significant increase in pulmonary resistance in the Amdur et al. (1978) study is in contrast to the 113 percent increase over pre-exposure values in total respiratory flow resistance measured in guinea pigs exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3 for 2 hr by Yokoyama (1969). Watanabe et al. (1973) also found increased pulmonary flow resistance in cats artificially ventilated through an endotracheal tube with 510, 980, or 1960 $\mu g/m^3$ (0.26, 0.50, or 1.00 ppm) of O_3 for 2 to 6.5 hr. Pulmonary resistance had increased to at least 110 percent of control values in all animals after 105 min of exposure to 510 $\mu g/m^3$ (0.26 ppm) of O_3, after 63 min of exposure to 980 $\mu g/m^3$ (0.50 ppm) of O_3, and after 49 min of exposure to 1960 $\mu g/m^3$ (1 ppm) of O_3. Dynamic lung compliance was decreased during O_3 exposure in the Watanabe et al. (1973) study, as it was in the Amdur et al. (1978) study. However, changes in pulmonary compliance measured by Watanabe et al. (1973) occurred less frequently and were less severe (based on percentage changes from pre-exposure control values) than changes in pulmonary resistance.

Like Amdur et al. (1978) and Yokoyama (1969), Murphy et al. (1964) also measured breathing pattern and respiratory flow resistance in guinea pigs during 2-hr O_3 exposures. These investigators found concentration-related increases in respiration rate during exposure to 666, 1333, 2117 or 2646 $\mu g/m^3$ (0.34, 0.68, 1.08, or 1.35 ppm) of O_3. Respiratory flow resistance was increased (to 148 and 170 percent of pre-exposure values) in guinea pigs exposed to 2117 and 2646 $\mu g/m^3$ (1.08 and 1.35 ppm) of O_3 respectively. Pulmonary compliance was not measured.

The variability in measurements of pulmonary resistance following O_3 exposure can be attributed to a number of factors including the following: frequency characteristics of the monitoring equipment and measurement techniques utilized, the influence of anesthetics, and the intraspecies differences in airway reactivity of guinea pigs. The latter point was the subject of critical review in the assessment of toxicological effects from particulate matter and sulfur oxides (U.S. Environmental Protection Agency, 1982).

Recovery of guinea pigs from short-term O_3 exposure was substantially different in the above three studies. Animals exposed by Amdur et al. (1978) showed little or no return toward pre-exposure values for any of the measured parameters during a 30-min recovery period following exposure. In guinea pigs exposed by Murphy et al. (1964) and Yokoyama (1969), respiration rates had returned almost to pre-exposure values by 30 min following exposure. The development of more persistent lung-function changes following O_3 exposure in the Amdur et al. study (1978) may be attributed to the small size and associated immaturity of these guinea pigs (200 to 300 g) compared with those in the studies by Murphy et al. (1964) (300 to 400 g) and Yokoyama (1969) (280 to 540 g). In an earlier study, Amdur et al. (1952) showed that young guinea pigs 1 to 2 months old were significantly more sensitive to inhaled sulfuric acid aerosols than 12- to 18-month-old animals. The use of ether anesthesia and placement of an intrapleural catheter by Amdur et al. (1978) but not by Murphy et al. (1964) or Yokoyama (1969) may also have sensitized the animals exposed by Amdur et al. (1978) to effects of O_3.

Inoue et al. (1979) exposed rabbits to 470 to 2156 $\mu g/m^3$ (0.24 to 1.1 ppm) of O_3 for 12 hr and performed lung function tests 6 hr, and 1, 3, and 7 days following exposure. These rabbits showed functional evidence of premature airway closure with increased trapped gas at low lung volumes 6 hr, 1 day, and 3 days following exposure. Functional changes indicating premature airway closure included increased values of closing capacity, residual volume, and closing volume. Lung quasistatic pressure-volume measurements showed higher lung volumes at lung distending pressures from 0 to -10 cm of H_2O. These lung function changes were greatest 1 day following exposure and had disappeared by 7 days following exposure. Distribution of ventilation in the lung was less uniform in O_3-exposed animals only at 6 hr following exposure. By 7 days following the initial 12-hr O_3 exposure, the only significant functional change was an increased lung distensibility in the midrange of lung volumes (from 25 to 75 percent total lung capacity).

Earlier studies by Yokoyama (1972), in which rabbits were exposed to 1 ppm of O_3 for 3 hr, showed a timing of lung function changes similar to that observed by Inoue et al. (1979). For both studies, maximum changes in O_3-exposed animals were observed 1 day following exposure and had disappeared by 7 to 14 days following exposure. However, in some aspects, the Yokoyama (1972) study was substantially different from that of Inoue et al. (1979). Yokoyama (1972) found reduced maximum lung volume at an air inflation pressure of 30 cm of H_2O, whereas Inoue et al. (1979) found no difference in maximum lung volume. Yokoyama (1972) does not show lung pressure-volume curves at pressures less than atmospheric pressure, so premature airway closure and gas trapping cannot be evaluated in this study. One factor that may contribute to differences between these two studies is the use of an excised lung preparation by Yokoyama

(1972) compared with evaluation of intact lungs in anesthetized rabbits by Inoue et al. (1979).

Yokoyama (1974) also evaluated lung function in rabbits following exposure to 1960 μg/m^3 (1 ppm) of O_3, 6 hr/day, for 7 to 8 days. He found increased pulmonary resistance and decreased dynamic compliance in O_3-exposed animals compared to air-exposed control animals. Static pressure-volume curves and maximum expiratory flow-volume curves were not significantly different between the two groups.

10.3.2.2 Long-Term Exposure. Table 10-3 summarizes results of long-term O_3 exposures. Raub et al. (1983a) exposed neonatal and adult (6-week-old) rats to 157, 235, or 490 μg/m^3 (0.08, 0.12, or 0.25 ppm) of O_3 12 hr/day, 7 days/week for 6 weeks. Lung function changes were observed primarily in neonatal rats following 6 weeks of O_3 exposure. Peak inspiratory flow measured in these animals during spontaneous respiration was significantly lower following exposure to 235 or 490 μg/m^3 (0.12 or 0.25 ppm) of O_3. Lung volumes measured at high distending pressures were significantly higher in neonatal animals exposed to 490 μg/m^3 (0.25 ppm) of O_3 for 6 weeks than in control animals. These results are consistent with increased lung volumes measured during lung inflation with either air or saline by Bartlett et al. (1974) following exposure of young rats (3- to 4-week-old) to 392 μg/m^3 (0.2 ppm) of O_3 continuously for 28 to 32 days. Moore and Schwartz (1981) also found an increased fixed lung volume (following lung perfusion at 30 cm inflation pressure with Karnovsky's fixative) after 180 days of continuous exposure to 980 μg/m^3 (0.5 ppm) of O_3. Yokoyama and Ichikawa (1974) found no change in lung static pressure-volume curves in mature rats exposed to 882 μg/m^3 (0.45 ppm) of O_3 6 hr/day, 6 days/week for 6 to 7 weeks.

Martin et al. (1983) studied the mechanical properties of the alveolar wall from rabbits exposed to 784 μg/m^3 (0.4 ppm) of O_3, 7 hr/day, 5 days/week for 6 weeks. A marked increase in the maximum extensibility of the alveolar wall and a greater energy loss with length-tension cycling (hysteresis) were found following exposure. A 15-percent increase in fixed lung volume following perfusion at 20 cm of H_2O was also reported following O_3 exposure, which is similar to the fixed lung volume changes reported by Moore and Schwartz (1981). Morphology and morphometry of paired lungs or lungs from animals similarly exposed to O_3 is reported in Section 10.3.1.4.

TABLE 10-3. EFFECTS OF OZONE ON PULMONARY FUNCTION: LONG-TERM EXPOSURES

Ozone concentration		Measurement[a,b] method	Exposure duration & protocol	Observed effects[c]	Species	Reference
μg/m³	ppm					
157 235 490	0.08 0.12 0.25	CHEM	6 weeks, 12 hr/day, 7 days/week	Increased end expiratory lung volume in adult rats and increased lung volumes at high distending pressures in neonatal rats exposed to 0.25 ppm of O_3. Reduced peak inspiratory flow in neonatal rats exposed to 0.12 or 0.25 ppm of O_3.	Rat (neonate or 6-week-old young adult)	Raub et al., 1983
392	0.2	MAST, NBKI	28 to 32 days, continuous	Increased lung distensibility in O_3-exposed rats at high lung volumes (95-100% TLC) during inflation with air or saline.	Rat (3 to 4 weeks)	Bartlett et al., 1974
392 1568 3920	0.2 0.8 2.0	UV or CHEM NBKI	62 exposures, 6 hr/day, 5 days/week	Increased R_L (not related to concentration) in rats exposed to 0.2 or 0.8 ppm of O_3. Lung volumes at high distending pressures (VC and TLC) were increased and FEF_{25} and FEF_{10} were decreased at 0.8 ppm of O_3.	Rat (10 weeks)	Costa et al., 1983
784	0.4	NBKI	6 weeks, 7 hr/day, 5 days/week	Increased alveolar wall extensibility at yield and break points, increased hysteresis ratio, and decreased stress at moderate extensions. Fixed lung volume increased 15%. Lung growth following pneumonectomy prevented these changes to O_3 exposure.	Rabbit	Martin et al., 1983
882	0.45	MAST	6 to 7 weeks, 6 hr/day, 6 days/week	No effect of exposure on lung pressure-volume curves.	Rat	Yokoyama and Ichikawa, 1974
980 1568	0.5 0.8	UV, NBKI	7, 28, or 90 days; 8 hr/day	Decreased quasistatic compliance (not related to concentration).	Monkey (Bonnet)	Eustis et al., 1981

TABLE 10-3. EFFECTS OF OZONE ON PULMONARY FUNCTION: LONG-TERM EXPOSURES (continued)

Ozone concentration µg/m³	Ozone concentration ppm	Measurement[a,b] method	Exposure duration & protocol	Observed effects[c]	Species	Reference
1254	0.64	UV, NBKI	1 year, 8 hr/day, 7 days/week	Following 6 months of exposure, ventilation was less homogeneous and R_L was increased. Following 12 months of exposure, R_L remained elevated and forced expiratory maneuvers showed small airway disfunction (decreased FEV_1 and $FEF_{12.5}$). During the 3-month recovery period following exposure, C_Lst decreased.	Monkey (Bonnet)	Wegner, 1982

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[a] Measurement method: MAST = KI-coulometric (Mast meter); CHEM = gas phase chemiluminescence; UV = UV photometry.

[b] Calibration method: NBKI = neutral buffered potassium iodide.

[c] See Glossary for the definition of pulmonary symbols.

Costa et al. (1983) evaluated lung function changes in rats exposed to 392, 1568, or 3920 μg/m^3 (0.2, 0.8, or 2 ppm) of O_3, 6 hr/day, 5 days/week for 62 exposure days. (This report will not discuss effects in animals exposed to 2 ppm of O_3). These investigators found increased pulmonary resistance (not concentration related) in rats exposed to 392 or 1568 μg/m^3 (0.2 or 0.8 ppm) of O_3. Lung volumes measured at high distending pressure (VC and TLC) were increased following exposure to 1568 μg/m^3 (0.8 ppm) of O_3. Similar changes in lung distensibility were observed by Raub et al. (1983a), Bartlett et al. (1974), Moore and Schwartz (1981), and Martin et al. (1983). Costa et al. (1983) also observed decreased (not concentration-related) maximum expiratory flows at low lung volumes (25 and 10 percent of VC) in rats exposed to 392 or 1568 μg/m^3 (0.2 or 0.8 ppm) of O_3. Changes in maximum flow at low lung volumes indicate peripheral airway dysfunction and may be related to decreased airway stiffness or narrowing of the airway lumen.

Eustis et al. (1981) evaluated lung function in bonnet monkeys (*Macaca radiata*) exposed to 980 or 1568 μg/m^3 (0.5 or 0.8 ppm) of O_3 8 hr/day for 7, 28, or 90 days. This study appeared to be preliminary (range finding) for the long-term study reported by Wegner (1982). Only a limited number of animals were evaluated at each time point (1 per exposure group at 7 days, 2 at 28 days, and 3 at 90 days). With so few animals tested and tests made following three different exposure periods, little significant lung-function data related to O_3 exposure were generated. When pooling results from all exposure times and O_3 concentrations, quasistatic lung compliance was significantly different in O_3-exposed animals than in control animals. Compliance tended to decrease from pre-exposure values in control animals and increase in O_3-exposed animals.

Wegner (1982) evaluated lung function in 32 bonnet monkeys, 16 of which were exposed to 1254 μg/m^3 (0.64 ppm) of O_3 8 hr/day, 7 days/week for 1 year. Lung function tests were performed pre-exposure, following 6 and 12 months of exposure, and following a 3-month postexposure recovery period. In addition to measurements of carbon monoxide diffusion capacity of the lungs (D_{LCO}), lung volumes, quasi-static pulmonary compliance ($C_{st(L)}$) and partial and maximum expiratory flow-volume curves by standard techniques, frequency dependence of compliance and resistance and pulmonary impedance from 2-32Hz were measured by a forced oscillation technique. The addition of these latter measurements may elucidate more clearly than ever before the site and nature of lung impairment caused by exposure to toxic compounds.

Following six months of O_3 exposure, pulmonary resistance and frequency dependence of pulmonary compliance were significantly increased. After 12 months, the O_3 exposure had significantly increased pulmonary resistance and inertance (related to the pressure required to accelerate air and lung tissue), and forced expiratory maneuvers showed decreased flows at low lung volumes (12.5 percent VC) and decreased volume expired in 1 sec (FEV_1). Wegner (1982) suggested that because lung volumes and pulmonary compliance were not affected in O_3-exposed animals, changes in forced expiratory function were more likely caused by narrowing of the peripheral airways than by decreased small airway stiffness. Rigid analysis of the pulmonary impedance data by linear-lumped-parameter modeling suggested that the increase in pulmonary resistance was due to central as well as peripheral airway narrowing.

During the 3-month recovery period following exposure, static lung compliance tended to decrease in both O_3-exposed and control animals. However, the decrease in compliance was significantly greater in O_3-exposed animals than in control animals. No other significant differences were measured following the 3-month recovery period, although values for O_3-exposed animals remained substantially different from those for control animals, suggesting that full recovery was not complete.

10.3.2.3 Airway Reactivity. Ozone potentiates the effects of drugs that constrict airway smooth muscle in mice, guinea pigs, dogs, sheep, and humans (Table 10-4). Early experimental evidence for hyperreactivity to bronchoconstrictive drugs following O_3 exposure was provided by Easton and Murphy (1967). Although much of their work was done with very high O_3 concentrations (9800 to 11760 $\mu g/m^3$, 5 to 6 ppm), they did show that mortality from a single subcutaneous injection of histamine was higher in guinea pigs exposed to 980 or 1960 $\mu g/m^3$ (0.5 or 1 ppm) of O_3 for 2 hr (33 and 50 percent mortality, respectively) compared with the mortality of air-exposed control animals. The animals appeared to die from massive bronchoconstriction, with the lungs remaining fully inflated instead of collapsing when the chest was opened.

Abraham et al. (1980) evaluated airway reactivity in sheep from measurements of pulmonary resistance following inhaled carbachol aerosols. Carbachol causes bronchoconstriction by stimulating airway smooth muscle at receptor sites that are normally stimulated by release of acetylcholine from terminals of the vagus nerve. Pulmonary resistance during inhalation of carbachol aerosols was significantly higher than pre-exposure values at 24 hr postexposure

TABLE 10-4. EFFECTS OF OZONE ON PULMONARY FUNCTION: AIRWAY REACTIVITY

Ozone concentration $\mu g/m^3$	Ozone concentration ppm	Measurement[a] method	Exposure duration & protocol	Observed effects[b]	Species	Reference
196 to 1568	0.1 to 0.8	CHEM	1 hr	Subcutaneous injection of histamine 2 hr following O_3 exposure caused a greater increase in R_L following exposure to 0.8 ppm of O_3 and a greater decrease in C_L dyn following exposure to all O_3 concentrations (magnitude of C_L changes not related to O_3 concentration).	Guinea pig (200-300 g)	Gordon and Amdur, 1980
196 1568	0.1 0.8	CHEM	1 hr	Decreased diaphragm and lung cholinesterase activity; parathion-treated animals had increased peak airway resistance compared to controls, but the difference was not statistically significant.	Guinea pig	Gordon et al., 1981
196 1960	0.1 1.0	MAST	10-30 min	Bilateral vagotomy: completely blocked increased peripheral lung resistance from 0.1 ppm of O_3 but not histamine; only partially blocked response from 1.0 ppm of O_3. Histamine-induced airway reactivity increased during 1.0 ppm but not 0.1 ppm of O_3 exposure and was not blocked by atropine or vagotomy.	Dog	Gertner et al., 1983a,b,c Kaplan et al., 1981
980	0.5	CHEM	2 hr	Increased number of mast cells and lymphocytes in tracheal lavage 24 hr after exposure.	Sheep	Sielczak et al., 1983
980 1568	0.5 0.8	MAST	Continuous, 13 to 16 days of O_3 exposure in four periods (3 to 5 days each) separated by 3 to 8 days of breathing air	Repeated exposures to 0.5 or 0.8 ppm of O_3 plus aerosolized ovalbumin resulted in greater mortality from anaphylactic shock produced by intravenojection of ovalbumin compared with effects of ovalbumin injection in mice repeatedly exposed to ovalbumin aerosols but no O_3.	Mouse	Osebold et al., 1980
980 2156	0.5 1.1	NBKI	2 hr	Increased histamine-induced mortality immediately following exposure to 0.5 or 1.1 ppm of O_3.	Guinea pig	Easton and Murphy, 1967
980 1960 3920	0.5 1. 2	CHEM	2 hr	Increased airway reactivity to aerosolized carbachol 24 hr but not immediately following exposure to 980 $\mu g/m^3$ (0.5 ppm) of O_3 with no change in R_L, FRC, C_L st, or tracheal mucous velocity. Increased R_L 24 hr following exposure and airway reactivity immediately and 24 hr following exposure (1 ppm).	Sheep	Abraham et al., 1980

TABLE 10-4. EFFECTS OF OZONE ON PULMONARY FUNCTION: AIRWAY REACTIVITY (continued)

Ozone concentration μg/m³	Ozone concentration ppm	Measurement[a] method	Exposure duration & protocol	Observed effects[b]	Species	Reference
1100 to 1666	0.56 to 0.85	CHEM	2 hr	Abnormal, rapid, shallow breathing in conscious dogs while walking on a treadmill following O_3 exposures. Maximal 1- to 3-hr postexposure, normal 24-hour postexposure. Abnormal breathing not affected by drug-induced bronchodilatation (inhaled isoproteronol) but abolished by vagal cooling. Increased respiration rate caused by inhalation of aerosolized histamine after O_3 exposure also blocked by vagal cooling but not by isoproteronol.	Dog	Lee et al., 1979
1313	0.67	CHEM	2 hr	Abnormal, rapid, shallow breathing during exposure to air containing low O_2 or high CO_2 immediately following O_3 exposure. Abnormal breathing not affected by inhaled atropine aerosols or inhaled isoproteronol aerosols but abolished by vagal cooling.	Dog	Lee et al., 1980
1372 to 2352	0.7 to 1.2	CHEM	2 hr	Greater increase in R_L caused by histamine aerosol inhalation 24 hr following O_3 exposure. No hyperreactivity to histamine 1 hr following O_3 exposure. Drug-induced bronchodilatation (inhaled isoproteronol) blocked any increase in R_L before or after O_3 exposure. Inhalation of atropine or vagal cooling (to block reflex bronchoconstriction) prevented O_3-induced reactivity to histamine.	Dog	Lee et al., 1977
1960 4312 5880	1.0 2.2 3.0	UV	2 hr	Marked increase in airway responsiveness to ACh and histamine 1 hr after exposure; increased to a lesser degree 1 day later, and returned to control levels by 1 week. Effects possibly linked to acute inflammatory response.	Dog	Holtzman et al., 1983a,b Fabbri et al., 1984

[a] Measurement method: MAST = KI-coulometric (Mast meter); CHEM = gas phase chemiluminescence; NBKI = neutral buffered potassium iodide.

[b] See Glossary for the definition of pulmonary symbols.

but not significantly higher than pre-exposure values at 24 hr postexposure but not immediately following a 2-hr exposure to 980 µg/m^3 (0.5 ppm) of O_3. This O_3 exposure did not affect resting end-expiratory lung volume (functional residual capacity) or static lung compliance. In sheep exposed to 1960 µg/m^3 (1 ppm) of O_3 for 2 hr, baseline resistance (before carbachol aerosol inhalation) was elevated 24 hr following exposure, and airway reactivity to carbachol was increased immediately and 24 hr following O_3 exposure.

Gordon and Amdur (1980) evaluated airway reactivity to subcutaneously injected histamine in guinea pigs following a 1-hr exposure to 196 to 1568 µg/m^3 (0.1 to 0.8 ppm) of O_3. Airway reactivity to histamine was maximal 2 to 6 hr following O_3 exposure and returned to control levels by 24 hr following exposure. The histamine-induced increase in pulmonary resistance was greater in guinea pigs exposed to 1568 µg/m^3 (0.8 ppm) of O_3 than in air-exposed control animals. Pulmonary compliance decreased more following histamine injection in all O_3-exposed groups than in air-exposed controls, but there were no differences in the the histamine-induced decreases in pulmonary compliance between any of the O_3 concentrations (from 196 to 1568 µg/m^3; 0.1 to 0.8 ppm).

Gordon et al. (1981) studied the effect of O_3 on tissue cholinesterases to see if they were responsible for the bronchial reactivity observed following challenges with bronchoconstrictor analogs of acetylcholine. Guinea pigs were exposed to clean air or 196 or 1,568 µg/m^3 (0.1 or 0.8 ppm) of O_3 for 1 hr. After 2 hr, brain, lung, and diaphragm samples were analyzed for cholinesterase activity. Brain cholinesterase activity was not affected, but lung cholinesterase underwent a 17 percent decrease in activity at 196 µg/m^3 (0.1 ppm) and a 16 percent decrease at 1,568 µg/m^3 (0.8 ppm). Ozone at 1,568 µg/m^3 (0.8 ppm) also decreased the diaphragm cholinesterase activity by 14 percent. To provide long-term inhibition of cholinesterase, guinea pigs were treated with parathion, an irreversible cholinesterase inhibitor. Airway resistance tended to increase following histamine challenge in the parathion-treated guinea pigs, but the difference was not statistically significant because of large variations in response. The authors suggested that cholinesterase inhibition by O_3 may contribute to the O_3-induced bronchial reactivity, as already reported. Presumably, the decreased cholinesterase activity could result in higher acetylcholine concentrations in the bronchial muscle. A cholinergic-related stimulus, such as occurs with O_3 exposure, should then increase the contraction of the bronchus. The persistence of this activity is not known.

Lee et al. (1977) evaluated airway reactivity in O_3-exposed dogs from changes in pulmonary resistance induced by histamine aerosol inhalation. Dogs were exposed to 1372 to 2352 $\mu g/m^3$ (0.7 to 1.2 ppm) of O_3 for 2 hr. Airway reactivity to inhaled histamine aerosols was significantly greater 24 hr but not 1 hr after O_3 exposure. Bronchodilatation induced by inhalation of isoproterenol aerosols prevented any change in resistance following histamine exposure. This experiment showed that the increased resistance normally observed following histamine exposure was caused by constriction of airway smooth muscle and not by edema or increased mucous production, which would not be prevented by isoproterenol bronchodilatation. Administration of atropine (which blocks bronchoconstrictor activity coming from the vagus nerve) or vagal cooling (which blocks both sensory receptor activity traveling from the lung to the brain and bronchoconstrictor activity going from the brain to the lung) decreased the response to histamine both before and following O_3 exposure and abolished the hyperreactive airway response. These experiments showed that the increased sensitivity to histamine following O_3 exposure was caused by heightened activity of vagal bronchoconstrictor reflexes.

Although the work of Lee et al. (1977) suggests that stimulation of vagal reflexes by histamine is responsible for the increased airway reactivity found in dogs following ozone exposure, Kaplan et al. (1981) found that local responses to histamine in the lung periphery may not be mediated by a significant vagal component. When monodispersed histamine aerosols were delivered to separate sublobar bronchi in dogs through a 5.5-mm-diameter fiber-optic bronchoscope, collateral airflow resistance increased both before and after bilateral cervical vagotomy. In follow-up studies that used similar techniques, Gertner et al. (1983a,b,c) described the role of vagal reflexes in the response of the lung periphery to locally administered histamine and O_3. Collateral resistance increased during separate 30-min exposures to either 196 $\mu g/m^3$ (0.1 ppm) of O_3 or 1.5 $\times 10^{-6}$ mg/m^3 of histamine. However, although parasympathetic blockade (atropine or bilateral cervical vagotomy) prevented the responses to O_3, it did not prevent the responses to histamine (Gertner et al., 1983b). In addition, a 30-min exposure to 196 $\mu g/m^3$ (0.1 ppm) of O_3 did not affect the airway responsiveness to histamine, but when the O_3 exposure was increased to 1960 $\mu g/m^3$ (1.0 ppm) for 10 min, histamine produced greater increases in collateral resistance that were not abolished by parasympathetic blockade (Gertner et al., 1983c). Exposure to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 for

30 min produced an increase in collateral resistance that was mediated by the parasympathetic system in the early phase of the response and related in part to histamine release in the late phase of the response (Gertner et al., 1983a). Results from this series of studies by Kaplan et al. (1981) and Gertner et al. (1983a,b,c) are difficult to interpret because of the small numbers of animals in each test group and large variations in response. In addition, because peripheral resistance contributes only a small part to total pulmonary resistance, the findings of these authors do not necessarily contradict the work of Lee et al. (1977). Rather, all the studies taken together suggest that the periphery of the lung may respond differently from the larger conducting airways during exposure to O_3 and that factors in addition to vagal bronchoconstrictor reflexes can produce an increased airway reactivity to histamine.

Holtzman et al. (1983a) reported the time course of O_3-induced airway hyperreactivity in dogs exposed to 1960 and 4312 $\mu g/m^3$ (1.0 and 2.2 ppm) of O_3 for 2 hrs. Airway responsiveness to acetylcholine in 7 dogs increased markedly 1 hr, to a lesser extent, 24 hr after exposure to 4312 $\mu g/m^3$ (2.2 ppm) of O_3, returning to control levels by 1 week after exposure. Ozone-induced increases in airway responsiveness to histamine were similar following exposure to 1960 $\mu g/m^3$ (1.0 ppm) of O_3, but data were reported for only 2 dogs. The authors suggested that the time course of the O_3 effect may be linked to acute airway inflammation. In a coincident publication, Holtzman et al. (1983b) found a strong association between airway hyperreactivity and tracheal inflammation in dogs 1 hr following a 2-hr exposure to 4116 $\mu g/m^3$ (2.1 ppm) of O_3. Airway reactivity was assessed from the increase in pulmonary resistance following inhalation of acetylcholine aerosols, and airway reactivity was increased in 6 of 10 O_3-exposed dogs. The number of neutrophils present in a tracheal biopsy, a measure of inflammation, was increased only in the 6 dogs that were hyperreactive to acetylcholine. These observations have recently been extended to show an association of O_3-induced increases in airway responsiveness with inflammation in more distal airways (Fabbri et al., 1984). The number of neutrophils as well as ciliated epithelial cells in fluid recovered from bronchoalveolar lavage was increased in 5 dogs that were hyperreactive to acetylcholine following a 2-hr exposure to 5880 $\mu g/m^3$ (3.0 ppm) of O_3. The results of tracheal lavage in sheep exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3 for 2 hr suggest that the migration of mast cells into the airways may also have important implications for reactive airways and allergic airway disease

(Sielczak et al., 1983). Nasotracheal-tube exposure to O_3 in 7 sheep resulted in an increased number of mast cells and lymphocytes 24 hr after exposure, suggesting an association between an enhanced inflammatory response and O_3-induced bronchial reactivity reported previously in sheep (Abraham et al., 1980). The relationship between airway inflammation and airway reactivity in other studies at lower concentrations of O_3 is not well understood.

Increased drug-induced bronchoconstriction is not the only indicator of airway hyperreactivity following O_3 exposure. Animal experiments were designed to investigate the mechanisms responsible for the abnormal, rapid, shallow breathing found in human subjects exercising during experimental O_3 exposure compared with subjects exercising in clean air (Chapter 11). Lee et al. (1979, 1980) showed that abnormal, rapid, shallow breathing in conscious dogs immediately following 2-hr exposures to 1100 to 1666 $\mu g/m^3$ (0.56 to 0.85 ppm) of O_3 was a hyperreactive airway response. This abnormal breathing pattern was elicited by mild exercise, histamine aerosol inhalation, or breathing air with reduced oxygen (O_2) or elevated carbon dioxide (CO_2) concentrations. The rapid, shallow breathing observed in dogs following O_3 exposure was not affected by drug-induced bronchodilatation (inhaled isoproteronol aerosols) or by blocking vagally induced bronchoconstriction with atropine. In all cases, rapid, shallow breathing was abolished by vagal cooling, which blocked the transmission of sensory nerves located in the airways. These investigators (Lee et al., 1979, 1980) suggest that the rapid, shallow breathing observed following O_3 exposure in dogs is caused by heightened activity of sensory nerves located in the airways. The increased reactivity of these sensory nerves is independent of smooth muscle tone (either bronchodilatation or bronchoconstriction).

Studies of lung morphology following O_3 exposure showed damage to the respiratory epithelium (Section 10.3.1). Damage to the epithelium overlying sensory receptors may be responsible for the increased receptor reactivity to mechanical stimulation (increased ventilation with exercise, low O_2, or high CO_2) or chemical (histamine) stimulation (Nadel, 1977; Boushey et al., 1980). The rapid, shallow breathing observed in experimental animals during O_3 exposures (Amdur et al. 1978; Yokoyama, 1969; Murphy et al., 1964) may also be related to increased sensory neural activity coming from the lungs, not to an indirect effect of changes in airway diameter or lung distensibility as previously speculated.

In their study of allergic lung sensitization, Osebold et al. (1980) showed additional functional evidence for epithelial disruption caused by O_3 exposure. These investigators studied the anaphylactic response of mice to intravenous ovalbumin injection following repeated inhalations of aerosolized ovalbumin. Mice were continuously exposed to 980 or 1568 $\mu g/m^3$ (0.5 or 0.8 ppm) of O_3 for four periods of 3 to 5 days each, separated by 3 to 8 days of ambient air exposure. During periods of O_3 exposure, mice were removed from the exposure chambers for short periods, and they inhaled ovalbumin aerosols for 30 min. Mice exposed to O_3 and ovalbumin aerosols developed more severe anaphylactic reactions and had a higher incidence of fatal anaphylaxis than air-exposed mice receiving the same exposure to aerosolized ovalbumin. In mice exposed to aerosolized ovalbumin, 34 percent of the O_3-exposed mice (1568 $\mu g/m^3$; 0.8 ppm) developed fatal anaphylaxis following intravenous ovalbumin injection, compared with 16 percent of the air-exposed animals. This study also showed some indication of an interaction between O_3 exposures and exposures to sulfuric acid aerosols. Of the mice exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3 plus 1 mg/m^3 of sulfuric acid aerosols, 55 percent died of anaphylactic shock following intravenous ovalbumin injection, compared with 20-percent mortality in mice exposed to O_3 alone and zero mortality in mice exposed to sulfuric acid aerosols alone. The authors propose that these data may indicate that pollutants can increase not only the total number of clinical asthma attacks, but also the number of allergically sensitized individuals in the population. Matsumura (1970) observed a similar increase in the allergic response of sensitized guinea pigs to inhaled antigen following 30 min of exposure to 2 ppm O_3.

10.3.3 Biochemically Detected Effects

10.3.3.1 Introduction. This section will include some studies involving concentrations above 1960 $\mu g/m^3$ (1 ppm) of O_3, because the direction of the effect is opposite that for lower O_3 concentrations (decrease vs. increase in many parameters). An extensive body of data on this topic has been reviewed by Menzel (1983), Mustafa et al. (1977, 1980, 1983), Mustafa and Lee (1979), Cross et al. (1976), and Chow (1983). To facilitate presentation of this information, it has been categorized by broad classes of metabolic activity. This results in some degree of artificial separation, particularly because many patterns of response to O_3 are similar across the classes of metabolism. Lung permeability is discussed in this section, because it is typically detected biochemically. The final subsection presents hypotheses about the molecular mechanism(s) of action of O_3, relying on the data presented earlier by metabolic class.

10.3.3.2 Antioxidant Metabolism. Antioxidant metabolism of the lungs is influenced by O_3 exposure. As shown in the schematic diagram below (Figure 10-3), this system consists of a number of enzymes. As shall be discussed, O_3 has been shown to produce several reactive oxidant species *in vitro* from compounds found in the lung, as well as in other organs. It is reasonably certain that O_3 can produce such reactive species in the lung after *in vivo* exposure. Many of these oxidant species are metabolized by the glutathione peroxidase system, rendering them less toxic. Thus, this system is involved in the toxicology of O_3.

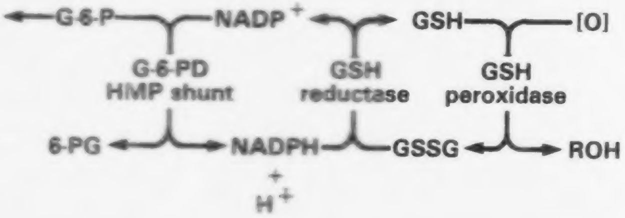

Figure 10-3. Intracellular compounds active in antioxidant metabolism of the lung. (G-6-P = glucose-6-phosphate; 6-PG = 6-phosphogluconate; G-6-PD = glucose-6-phosphate dehydrogenase; HMP shunt = hexose monophosphate shunt; NADP+ = nicotinamide adenine dinucleotide phosphate; NADPH = reduced NADP; GSH = glutathione; GSSG = glutathione disulfide; [O] = oxidizing moiety [i.e., hydrogen peroxide, free radical, lipid peroxide]; GSH peroxidase = glutathione peroxidase; GSH reductase = glutathione reductase; and ROH = reduced form of [O]).
Source: U.S. Environmental Protection Agency (1978).

Typically, following exposures to levels of O_3 below 1960 $\mu g/m^3$ (1 ppm), the activities of most enzymes in this system are increased (Table 10-5). Whether this increase is due to direct mechanisms (e.g., *de novo* synthesis resulting in greater enzyme activity), indirect mechanisms (e.g., an increased number of type 2 cells that naturally have a higher enzymic activity than type 1 cells), or a combination of both has not been proven. The increase in type 2 cells is most likely to be the mechanism, because with similar exposure

TABLE 10-5. CHANGES IN THE LUNG ANTIOXIDANT METABOLISM AND OXYGEN CONSUMPTION BY OZONE

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
μg/m³	ppm					
196	0.1	NBKI	Continuous for 7 days	With vit E-deficient diet, increased levels of GSH and activities of GSH peroxidase, GSH reductase, and G-6-PD; no effect on malic dehydrogenase. With 11 ppm vit E diet, increased levels of GSH peroxidase and G-6-PD. With 110 ppm vit E diet, no change.	Rat	Chow et al., 1981
196 392	0.1 0.2	I	Continuous for 7 days	With 66 ppm vit E-supplemented diet, increase in oxygen consumption of lung homogenates only at 0.2 ppm. With 11 ppm vit E-supplemented diet, increase in O_2 consumption at 0.1 and 0.2 ppm. Increase due to increased amount of mitochondria in lungs.	Rat	Mustafa, 1975 Mustafa and Lee, 1976
196 392	0.1 0.2	MAST, NBKI	Continuous for 7 days	Increased activities of GSH peroxidase, GSH reductase, and G-6-PD and of NPSH levels with (66 mg/kg) or without (11 mg/kg) vit E supplementation; at 0.2 ppm, effects less with vit E supplementation. Morphological lesions unaffected by vit E supplementation.	Rat	Plopper et al., 1979
392 980 1568	0.2 0.5 0.8	I	Continuous for 7 days; or 8 hr/day for 7 days	For the continuous exposure to the two higher concentrations, increased activities GSH peroxidase, GSH reductase, and G-6-PD. At the lower concentration (continuous), increased activities of GSH peroxidase and GSH reductase. A linear concentration-related increase in all three enzyme activities. Increased O_2 consumption using succinate-cytochrome C reductase activity fairly proportional to O_3 level. Similar results for intermittent exposure groups.	Rat	Mustafa and Lee, 1976
1568	0.8		Continuous for 1 to 30 days	Increased rates of O_2 consumption, reaching a peak at day 4 and remaining at a plateau for the remainder of the 30 days. Also an initial decrease (day 1) and a subsequent increase (day 2) in activity of succinate-cytochrome C reductase which plateaued between days 3 to 7.		

TABLE 10-5. CHANGES IN THE LUNG ANTIOXIDANT METABOLISM AND OXYGEN CONSUMPTION BY OZONE (continued)

Ozone concentration µg/m^3	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
392 686 980 1568	0.2 0.35 0.5 0.8	I	8 hr/day for 7 days	Increased concentration-related activities of G-6-PD, NADPH-cytochrome c reductase, and succinate oxidase. Significant increases occurred in the bonnet monkey at 0.35 and 0.5 ppm; in the rhesus monkey at 0.8 ppm. However, actual data were only reported for succinate oxidase.	Monkey,	Mustafa and Lee, 1976
392 980 1568	0.2 0.5 0.8	NBKI	Continuous for 8 days or 8 hr/day for 7 days	For continuous exposure to two higher concentrations, increased activities of GSH peroxidase, GSH reductase, and G-6-PD. At the lower concentration (continuous), increased activities of GSH peroxidase and GSH reductase. A concentration-related linear increase in all three enzyme activities. Similar results obtained for intermittent exposure groups.	Rat	Chow et al., 1974
392 980 1568	0.2 0.5 0.8	MAST, NBKI	8 or 24 hr/day for 7 consecutive days	Activities of G-6-PD and NADPH-cytochrome C reductase and succinate oxidase increase in a concentration-dependent fashion. No significant differences between the intermittent and continuous exposure groups.	Rat	Schwartz et al., 1976
392 980 1960	0.2 0.5 1.0	NBKI	3 hr/day for 4 days	Reduced glutathione levels increased in a linear concentration-dependent manner. No effect at 0.2 ppm in the no-exercise group. Exercise enhanced effect.	Mouse	Fukase et al., 1978
392 980 1960	0.2 0.5 1.0	ND	4 hr/day for up to 30 days	GSH content increased directly with O_3 concentration and exposure duration. Increase in activities of G-6-PD, GSH reductase, and GSH peroxidase after 7 days of exposure to 0.5 and 1 ppm.	Mouse	Fukase et al., 1975
2352- 16,072	1.2- 8.2		4 hr	Decrease in GSH content after exposure to 8.2 ppm. No change below 4.0 ppm. Two days postexposure to 4 ppm, GSH content increased, lasting for several days.		

TABLE 10-5. CHANGES IN THE LUNG ANTIOXIDANT METABOLISM AND OXYGEN CONSUMPTION BY OZONE (continued)

Ozone concentration µg/m^3	Ozone concentration ppm	Measurement^{a,b} method	Exposure duration and protocol	Observed effect(s)^c	Species	Reference
392 980 1568	0.2 0.5 0.8	MAST, NBKI	8 or 24 hr/day for 7 days	All O_3 levels: increase in NPSH levels; increased activities of G-6-PD, GSH reductase, NADH cyt. c reductase. At 0.5 and 0.8 ppm, increased activity of succinate cyt. c reductase. At 0.8 ppm, continuous increase began at day 2 of exposure.	Rat	DeLucia et al., 1975a
1568	0.8		8 hr/day for 7 days	Increased NPSH, GSH, and G-6-PD; no change in other enzymes.	Monkey	
3920 7840	2 4		2 to 8 hr	Loss of GSH; loss of SH from lung mitochrondrial and microsomal fractions and inhibition of marker enzyme activities from these fractions.	Rat	
392 980 1568	0.2 0.5 0.8	I	Continuous for 7 days	Concentration-related increase in O_2 consumption.	Rat	Mustafa et al., 1973
627	0.32	UV	6 hr	In both vit E-supplemented and nonsupplemented groups: increased G-6-PD activities and GSH levels; decreased ACHase activities.	Mouse	Moore et al., 1980
882	0.45	UV	Continuous for 5 days	Mice: increased levels/activities of TSH, NPSH, GSH peroxidase, GSH reductase, G-6-PD, 6-P-GD, isocitrate dehydrogenase, cytochrome c oxidase, and succinate oxidase. Rats: increased levels/activities of NPSH, GSH peroxidase, and G-6-PD in several strains. Generally mice were more responsive. For both species, no change in DNA or protein levels or activity of GSH-S-transferase.	Mouse, 3 strains of rats	Mustafa et al., 1982
882	0.45	UV	8 hr/day for 7 days	O_3 and 4.8 ppm of NO_2 alone produced no significant effects but O_3 + NO_2 produced synergistic effects: increased total and nonprotein sulfhydryls; increased activities of succinate oxidase and cytochrome c oxidase.	Mouse	Mustafa et al., 1984

TABLE 10-5. CHANGES IN THE LUNG ANTIOXIDANT METABOLISM AND OXYGEN CONSUMPTION BY OZONE (continued)

Ozone concentration µg/m^3	ppm	Measurement^{a,b} method	Exposure duration and protocol	Observed effect(s)^c	Species	Reference
882	0.45	ND	Continuous for 7 days	Increased SOD activity at days 3 and 5, but not days 2 and 7 of exposure.	Rat	Bhatnagar et al., 1983
980	0.5	NBKI	8 hr/day for 7 days	Increases in activities of GSH peroxidase, GSH reductase and G-6-PD and in GSH levels of rats. No effect in monkeys.	Rat Monkey	Chow et al., 1975
1372	0.7	NBKI	Continuous for 5 days	Increased activities of GSH peroxidase, G-6-PD, and GSH reductase. Malonaldehyde observed.	Rat	Chow and Tappel, 1972
1568	0.8		Continuous for 7 days	The increases in the first two enzymes were partially inhibited as a logarithmic function of vitamin E levels in diet.		
1470	0.75	NBKI	Continuous for up to 30 days	Increase in activities of GSH peroxidase, GSH reductase, G-6-PD, 6-P-GD, and pyruvate kinase at day 3, reaching a peak at day 10, at which time beginning of a slight decrease (except for GSH peroxidase which continued to increase). At day 30 still elevated over controls.	Rat	Chow and Tappel, 1973
1568	0.8		Continuous for 7 days	Increased activities of hexose monophosphate shunt and glycolytic enzymes of lung.		
1568	0.8	NBKI	Continuous for 3 days	Increased activities of GSH peroxidase, GSH reductase, and G-6-PD; levels of NPSH; general protein synthesis; and rate of mitochondrial succinate oxidation. Decrease to control values 6 to 9 days postexposure. Re-exposure using same regimen (6, 13, or 27 days postexposure) resulted in similar elevations.	Rat	Chow et al., 1976b
1568	0.8	I	Continuous for 10 to 20 days	At the higher concentration: increase in the lung mitochondrial O_3 consumption in oxidation of 2-oxyglutarate and glycerol-1-phosphate and the number of type 2 alveolar cells which are rich in mito-	Rat	Mustafa et al., 1973
3920	2		8 hr	chondria. No change in malonaldehyde. At the lower concentration: increase in O_2 consumption.		

TABLE 10-5. CHANGES IN THE LUNG ANTIOXIDANT METABOLISM AND OXYGEN CONSUMPTION BY OZONE (continued)

Ozone concentration μg/m³	ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
1568	0.8		< 24 hr	NPSH level unaffected at 0.8 ppm of O_3 for < 24 hr or or 1.5 ppm for < 8 hr; decreased at 2 ppm of O_3 for 8 hr or 4 ppm for 6 hr. At 4 ppm of O_3 for 6 hr, decreased level of GSH; no change in GSSG level.	Rat	DeLucia et al., 1975b
2940-7840	1.5-4		< 8 hr			
1568	0.8	I	10 days	Lung SH levels unchanged. Increase in G-6-PD and and cytochrome c reductase activities. No change in malonaldehyde levels.	Rat	DeLucia et al., 1972
3920	2		4 to 8 hr	Decrease in lung SH levels and in G-6-PD, GSH reductase, and cytochrome c reductase activities. No change in malonaldehyde levels.		
3920-5880	2-3		30 min	In vitro: decrease in SH levels; increase in malonaldehyde levels.		
1568	0.8	ND	Continuous for 7 days	Increased activity of superoxide dismutase.	Rat	Mustafa et al., 1977
1568	0.8	UV	92 hr	Succinate oxidase, cytochrome c oxidase, and isocitrate dehydrogenase: No effect at 24 days old, increased in 90-day-old rats. G-6-PD, 6-PGH: increased at 24 and 90 days of age, latter had greater increase. Succinate oxidase and G-6-PD decreased in 7- and 12-day-old rats and increased in 18-day-old rats. High mortality in 7- and 12-day-old rats.	Rat (7 to 90 days old)	Elsayed et al., 1982a
1568	0.8	UV	Continuous for 5 days	Diet was constant vitamin E and deficient or supplemented (2 levels) with selenium (Se). No change in GSH peroxidase. With 0 Se, decreased GSH reductase activity; no change with low or high Se. Progressive increase in activities of G-6-PD and 6-P-GD with increasing Se, beginning at low Se level.	Mouse	Elsayed et al., 1982b

TABLE 10-5. CHANGES IN THE LUNG ANTIOXIDANT METABOLISM AND OXYGEN CONSUMPTION BY OZONE (continued)

Ozone concentration µg/m³	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
1568	0.8	UV	Continuous for 5 days	Diet was constant vitamin E and 0 ppm of Se or 1 ppm in Se. +Se: increased G-6-PD, 6-P-GD; no change in GSH reductase or GSH peroxidase. -Se: decreased GSH reductase. Both diet groups had increase in TSH and NPSH, and lung Se levels after O_3.	Mouse	Elsayed et al., 1983
1568	0.8	NBKI	continuous for 7 days	Vitamin E partially prevented increased activities of G-6-PD, 6-P-GD, and malic enzyme. Activities of phosphofructokinase and pyruvate kinase increased. No effect on aldolase and malate dehydrogenase.	Rat	Chow and Tappel, 1973
1764	0.9	CHEM	96 hr	Trend towards decreased activities of GSH reductase GSH peroxidase, G-6-PD before 18 days of age, followed by increases thereafter. For G-6-PD: no change at 5 and 10 days of age; decrease at 15 days, and increase at 25 and 35 days.	Rat (5-180 days old)	Tyson et al., 1982
1764	0.9	MAST	≥ 96 hr	96 hr: No effect below 20 days of age; G-6-PD increases thereafter up to 35 days, after which (40 and 50 days old) it decreases. When exposure started at 25 or 32 (but not 10 to 15) days of age, the maximal increase in G-6-PD occurred at about 32 days of age under continuous exposure conditions.	Rat (10-50 days old)	Lunan et al., 1977

[a] Measurement method: MAST = KI-coulometric (Mast meter); NBKI = neutral buffered potassium iodide; CHEM = gas solid chemiluminescence; UV = UV photometry; I = iodometric; ND = not described.

[b] Calibration method: NBKI = neutral buffered potassium iodide.

[c] Abbreviations used: GSH = glutathione; GSSG = reduced glutathione; G-6-PD = glucose-6-phosphate dehydrogenase; LDH = lactate dehydrogenase; NPSH = non-protein sulfhydryls; SH = sulfhydryls; 6-P-GD = 6-phosphogluconate dehydrogenase.

regimens, the effects (increased enzyme activities and increased numbers of type 2 cells) increase, reaching a maximum at 3 to 4 days of exposure and a steady state on day 7 of exposure. Whatever the mechanism, the increase occurs at low O_3 levels in several species under varying exposure regimens (Table 10-5). The net result is that the antioxidant metabolism of the lung is increased. Whether this is a protective or a toxic response is often debated. To resolve this debate scientifically will require more knowledge of the mechanisms involved. However, even attributing it to be a protective response implies a physiological need for protection (e.g., an initial toxic response occurred which required protection). A more detailed discussion of these effects follows.

Acute exposures to high concentrations of O_3 generally decrease antioxidant metabolism, whereas repeated exposures to low levels increase this metabolism. For example, DeLucia et al. (1975a) compared the effects of acute (2 to 8 hr) exposures to high O_3 levels (3920 and 7840 $\mu g/m^3$, 2 and 4 ppm) and short-term (8 or 24 hr/day, 7 days) exposures to lower O_3 levels (392, 980, 1568 $\mu g/m^3$, 0.2, 0.5, 0.8 ppm) on rats. For nonprotein sulfhydryl levels (principally glutathione, GSH), decreases in the level of GSH were progressive with time of exposure (2 to 6 hr) to 7840 $\mu g/m^3$ (4 ppm). For glutathione disulfide (GSSG), decreases were less and had returned to normal by 6 hr of exposure. These exposure regimens also decreased the activities of GSH reductase and glucose-6-phosphate dehydrogenase (G-6-PD). After the first day of a 7-day continuous exposure to 1568 $\mu g/m^3$ (0.8 ppm) of O_3, no significant change was seen in the nonprotein sulfhydryl or GSH content or in the activities of G-6-PD, GSH reductase, or disulfide reductase. However, the levels/ activities of these constituents increased by day 2 and remained elevated for the remainder of the exposure period. Comparable results were reported with similar (but not identical) exposure regimens by DeLucia et al. (1972, 1975b) using rats and Fukase et al. (1975) using mice.

Investigators (Table 10-5) have found that for lower levels of O_3, increases in antioxidant metabolism are linearly related to O_3 concentration. Most such studies were conducted by using intermittent and continuous exposures. No differences between these regimens were found, suggesting that concentration of exposure is more important than time of exposure.

Chow et al. (1974) exposed rats continuously or intermittently (8 hr/day) for 7 days to 392, 980, or 1568 $\mu g/m^3$ (0.2, 0.5, or 0.8 ppm) of O_3 and found a concentrated-related linear increase in activities of GSH peroxidase, GSH reductase, and G-6-PD. Significant increases occurred for all measurements, except G-6-PD at continuous exposure to 392 μg/m^3 (0.2 ppm). Although the difference between continuous and intermittent exposure was not examined statistically, no major differences appeared to exist. Schwartz et al. (1976) made similar observations for G-6-PD activity when using identical exposure regimens and found concurrent morphological changes (Section 10.3.1). Mustafa and Lee (1976), also by using identical exposure regimens, found similar effects for G-6-PD activity. DeLucia et al. (1975a) found similar changes and increased nonprotein sulfhydryls at all three concentrations of O_3. A similar study was performed in mice by using a longer exposure period of 30 days (Fukase et al., 1975). The increase in GSH level was related to concentration and time of exposure. Fukase et al. (1978) also observed a linear concentration-related increase in GSH levels of mouse lungs exposed 3 hr/day for 4 days to 392, 980, or 1960 μg/m^3 (0.2, 0.5, or 1.0 ppm) of O_3. Exercise enhanced the effect. At the lower O_3 level, the increase in GSH was significant only in the exercising mice.

The influence of time of exposure was examined directly by Chow and Tappel (1973). Rats were exposed continuously to 1470 μg/m^3 (0.75 ppm) for 1, 3, 10, or 30 days, at which times measurements of GSH reductase, GSH peroxidase, G-6-PD, pyruvate kinase, and 6-phosphogluconate dehydrogenase activities were made. No statistical tests or indications of data variability were presented. A few of the enzyme activities (GSH peroxidase and 6-phosphogluconate dehydrogenase) may have decreased at day 1 of exposure. All enzyme activities except GSH peroxidase had increased by day 3 and reached a peak at 10 days and then began to return toward control values. GSH peroxidase activity continued to increase over this time of exposure. In a similar study (Mustafa and Lee, 1976), G-6-PD activity was measured after rats were exposed for 7 days to 1568 μg/m^3 (0.8 ppm) continuously. No effect was detected on day 1, but by day 2 the activity had increased. The peak response was on day 4; the activity remained elevated to an equivalent degree on day 7. In a similar experiment, DeLucia et al. (1975a) obtained equivalent results.

The tolerance phenomenon has also been investigated for lung antioxidant metabolism. Rats were exposed continuously for 3 days to 1568 μg/m^3 (0.8 ppm) of O_3, allowed to remain unexposed for 6, 13, or 27 days, and then re-exposed for 3 days to the same O_3 level (Chow et al., 1976b). Immediately after the first 3 days of exposure, the activities of GSH peroxidase, GSH reductase, and G-6-PD were increased, as was the nonprotein sulfhydryl content. By 2 days after this exposure ceased, recovery had begun; control values were completely reached by 9 days postexposure. Following a 30-day recovery period, no changes were observed. When re-exposure commenced on day 6 of recovery (at which time incomplete recovery was observed), the metabolic activities returned to levels equivalent to those of the original exposures. Similar findings were made when re-exposure commenced on days 13 and 27 days of the recovery period.

The influence of vitamin E, an antioxidant, on O_3 toxicity has been extensively studied, because it typically reduces the toxicity of O_3 in animals. This topic has been recently reviewed by Chow (1983). Early studies centered on mortality. For example, vitamin E-deficient rats are more susceptible to continuous exposure to 1960 $\mu g/m^3$ (1 ppm) of O_3 than rats fed supplements of vitamin E (LT50, the time at which a 50 percent mortality is observed, 8.2 days versus 18.5 days) (Roehm et al., 1971a, 1972). Vitamin E protected animals from mortality and changes in the wet to dry weight ratios of the lung (lung edema) on continuous exposure to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 or higher for 7 days (Fletcher and Tappel, 1973). Vitamin E protection against O_3 is positively correlated to the log concentration of dietary vitamin E fed to the rats. Rats maintained on vitamin E-supplemented diets and exposed to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 continuously for 7 days also had changes in 6-phosphogluconate dehydrogenase activity. Rats were exposed to 1372 to 31,360 $\mu g/m^3$ (0.7 to 16 ppm) of O_3 while being fed diets containing ascorbic acid, dl-methionine, and butylated hydroxytoluene (Fletcher and Tappel, 1973). This combination was supposed to be a more potent antioxidant mixture than vitamin E alone. Animals fed diets with the highest level of this antioxidant mixture had the greatest survival rate. Animals fed α-tocopherol (vitamin E) in the range of 10 to 150 mg/kg of diet had a survival rate slightly lower than those fed the combination of antioxidants.

Donovan et al. (1977) fed mice 0 (deficient diet), 10.5 (minimal diet), or 105 (supplemental diet) mg/kg of vitamin E acetate. The diet was also altered to increase the peroxidizability of the lung by feeding either low or high polyunsaturated fats (PUFA). Mice were continuously exposed to 1960 $\mu g/m^3$ (1 ppm) of O_3. The mortality (LT50 of 29 to 32 days) was the same, regardless of the large differences in peroxidizability of the lungs of animals fed high- or low-PUFA diets. High supplemental levels (105 mg/kg) of vitamin E acetate were protective and delayed the LT50 to O_3 by an average of 15 days. Although these experiments demonstrate clearly the protective effect of vitamin E against O_3 toxicity, they do not support the hypothesis that changes in fatty acid composition of the lung will increase O_3 toxicity. The results could be interpreted to indicate that the scavenging of radicals by vitamin E is more important than the relative rate of oxidation of PUFA. These findings led to biochemical studies that used graded levels of dietary vitamin E.

Plopper et al. (1979) correlated biochemical and morphological (Section 10.3.1) effects in rats maintained on a synthetic diet with 11 mg kg/vitamin E (equivalent to the average U.S. adult intake) or commercial rat chow having 66 mg/kg vitamin E. The 11 mg/kg vitamin E group was exposed continuously for 7 days to 196 or 392 $\mu g/m^3$ (0.1 or 0.2 ppm) of O_3, and measurements were made at the end of exposure. The rats on the commercial diet were exposed to only the higher concentration. All exposures increased activities of GSH peroxidase, GSH reductase, and G-6-PD, and the amount of nonprotein sulfhydryl. Although statistical comparisons between the dietary groups were not made, greater increases appear to have occurred in the 11 mg/kg vitamin E group; the magnitude of the responses in the higher vitamin E group at 392 $\mu g/m^3$ (0.2 ppm) of O_3 was roughly equivalent to the magnitude of the responses of the low vitamin E group exposed to 196 $\mu g/m^3$ (0.1 ppm). The 2 dietary groups showed little variation in morphological effects.

These studies were expanded to include three vitamin E dietary groups: 0, 11, or 110 ppm (Chow et al., 1981). Rats were exposed to 196 $\mu g/m^3$ (0.1 ppm) of O_3 continuously for 7 days. In the 0-ppm vitamin E group, O_3 increased the level of GSH and the activities of GSH peroxidase, GSH reductase, and G-6-PD. Increases of similar magnitude occurred in the 11-ppm vitamin E group, with the exception of GSH reductase activity, which was not affected. In the highest vitamin E group, no significant effects were observed. Ozone caused no changes in the activity of malic dehydrogenase in any of the dietary groups. Morphologically (Section 10.3.1), only 1 of 6 rats of the 110-ppm vitamin E group had lesions, whereas more rats of the two other groups had lesions. These lesions became more severe as the vitamin E level decreased. They occurred at the bronchio-alveolar junction and were characterized by disarrangement of the bronchiolar epithelium and an increase in the number of alveolar macrophages.

Chow and Tappel (1972) exposed rats continuously to 1372 μg/m^3 (0.7 ppm) of O_3 for 5 days. The animals had been maintained on diets with different levels of dl-α-tocopherol acetate (vitamin E) (0, 10.5, 45, 150, and 1500 mg/kg diet). Ozone exposure increased GSH peroxidase, GSH reductase, and G-6-PD activities. For GSH peroxidase and G-6-PD activities, the increase was reduced as a function of the logarithmic concentration of vitamin E. Vitamin E did not alter the magnitude of the effect on GSH reductase, a finding in contrast to the results of others (Chow et al., 1981; Plopper et al., 1979). Malonaldehyde, which is produced by lipid peroxidation, increased; this increase was also partially inhibited as a logarithmic function of vitamin E concentration. However, others (DeLucia et al., 1972; Mustafa et al., 1973) have not observed the presence of malonaldehyde in exposed lungs. The increase in malonaldehyde and activity of GSH peroxidase were linearly correlated, leading Chow and Tappel (1972) to propose a compensatory mechanism in which the increase in GSH peroxidase activity increases lipid peroxide catabolism.

Chow and Tappel (1973) observed the typical protection of vitamin E (0 and 45 mg/kg diet α-tocopherol) from the effect of O_3 (1568 μg/m^3, 0.8 ppm; 7 days, continuous) on increasing G-6-PD activity in rat lungs. Similar findings occurred for 6-phosphogluconate dehydrogenase and malic enzyme activities. The activities of two glycolytic regulating enzymes, phosphofructokinase and pyruvate kinase, were increased by O_3 exposure but were not influenced by vitamin E levels in the diet. Aldolase and malate dehydrogenase activities were not affected.

Elsayed et al. (1982b, 1983) examined the influence of selenium (Se) in the diet on GSH peroxidase activity in the lung. Selenium is an integral part of one form of the enzyme GSH peroxidase. Mice were raised on a diet containing 55 ppm vitamin E with either 0 ppm or 1 ppm of Se and exposed to 1568 ± 98 μg/m^3 (0.8 ppm) of O_3 continuously for 5 days. In these mice, Se deficiency caused a sevenfold decline in Se level and a threefold decline in GSH peroxidase activity in the lung. Other enzyme activities (e.g., GSH reductase, G-6-PD, 6-phosphogluconate dehydrogenase) were not affected by dietary Se. After O_3 exposure, the GSH peroxidase activity in the Se-deficient group remained unstimulated and was associated with a lack of stimulation of GSH reductase, G-6-PD, and 6-phosphogluconate dehydrogenase activities. In contrast, the O_3-exposed Se-supplemented group exhibited increases in 6-phosphogluconate dehydrogenase and G-6-PD activities. Dietary deficiency or supplementation of Se, vis-a-vis alteration of GSH peroxidase activity, did not appear to influence the effects of O_3 exposure as assessed by other parameters. Although the animals received the same level of dietary vitamin E, after air or O_3 exposure, the Se-deficient group showed a two-fold increase in lung vitamin E levels relative to the Se-supplemented group, suggesting a complementary relationship between Se and vitamin E in the lung. This sparring action between Se (i.e., GSH peroxidase activity) and vitamin E might explain similar effects of O_3 exposure in Se-deficient and supplemented mice.

Several investigators have studied the responsiveness of different species to the effect of O_3 on antioxidant metabolism. DeLucia et al. (1975a) exposed both Rhesus monkeys and rats for 7 days (8 hr/day) to 1568 $\mu g/m^3$ (0.8 ppm). The nonprotein sulfhydryl and GSH content were increased, as was G-6-PD activity. Activity of GSH reductase was affected in the rats but not the monkeys. No statistical comparisons were made between the rats and monkeys. In the only parameter for which sufficient data were presented for comparison, G-6-PD, the increase in monkeys was about 125 percent of controls; for rats, it was about 130 percent of controls.

Rats and Rhesus monkeys were compared more extensively by Chow et al. (1975). Animals were exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3 8 hr/day for 7 days. The nonprotein sulfhydryl content and the activities of GSH peroxidase, GSH reductase, and G-6-PD increased in rats but not in monkeys. The magnitude of the increases in rats was 20 to 26 percent. The increases in monkeys were between 10 and 15 percent and statistically insignificant, "because of relatively large variations," according to the authors. The variation in the monkeys was approximately double that of the rats. The sample size of the monkeys (6) was lower than that of the rats (8). Statistical tests of the Type II error (e.g., false negative error) rates were not reported. Thus, the monkeys apparently were not affected to the same degree as the rats. However, the experiments with monkeys were apparently not conducted with as much statistical power as those with rats. Thus, under the actual study designs used, ozone would have had to have substantially greater effects on monkeys than rats for a statistically significant effect to be detected. This did not happen, leading to the conclusion of the investigators that monkeys are not more responsive. Studies of improved experimental design would indicate more definitively whether monkeys are less responsive. Mustafa and Lee (1976) also alluded to different G-6-PD responses of rats and Bonnet and Rhesus monkeys after exposures for 8 hr/day for 7 days to levels as low as 392 $\mu g/m^3$ (0.2

ppm). However, no data for G-6-PD were presented, and the description of these results was incomplete.

Mice (Swiss Webster) and 3 strains of rats (Sprague-Dawley, Wistar, and Long Evans) were compared after a 5-day continuous exposure to 882 $\mu g/m^3$ (0.45 ppm) of O_3 (Mustafa et al., 1982). Total sulfhydryl content increased only in mice. However, nonprotein sulfhydryl content increased in both rats and mice to a roughly equivalent degree. GSH-S-transferase was not affected in any of the animals. Mice exhibited the typical increases in the activities of GSH peroxidase, GSH reductase, G-6-PD, 6-phosphogluconate dehydrogenase, and isocitrate dehydrogenase. Rats were less affected; no changes were seen in the activities of GSH reductase or isocitrate dehydrogenase, and not all strains of rats showed an increase in the activities of GSH peroxidase, G-6-PD, and 6-phosphogluconate dehydrogenase. For GSH reductase and G-6-PD, the increased activities in exposed mice were significantly greater than the increased activities in exposed rats.

At present, it is not possible to determine whether these apparent species differences in responsiveness were due to differences in the total deposited dose of O_3, an innate difference in species sensitivity, or differences in experimental design (e.g., small sample sizes, insufficient concentration-response studies).

Age-dependent responsiveness to O_3-induced changes in GSH systems has been observed. Tyson et al. (1982) exposed rats (5 to 180 days old) to 1764 $\mu g/m^3$ (0.9 ppm) of O_3 continuously for 96 hr, except for suckling neonates (5 to 20 days old) which received an intermittent exposure (4 hr of exposure, 1.5 hr no exposure, 4 hr exposure). Given that others (Mustafa and Lee, 1976; Chow et al., 1974; Schwartz et al., 1976) have observed no differences between continuous and intermittent exposures for these enzymatic activities, this difference in regimen can be considered inconsequential. All ages given are ages at the time of initiation of exposure. They were calculated from those given in the report to facilitate comparisons with other reports on age sensitivity. Weanlings (25 and 35 days old) and nursing dams (57 and 87 days old) had higher lung to body weight ratios. Generally, the DNA content of the younger animals was unchanged. When the activities of G-6-PD, GSH reductase, and GSH peroxidase were measured after O_3 exposure, the trend was a decrease in activities at and before 18 days of age, followed by increases thereafter. For G-6-PD, this trend was most pronounced; at 5 and 10 days of age, no significant changes were seen; at 15 days of age, a decrease was seen; and at 25 and 35 days of age, progressively greater increases were seen.

Ten- to 50-day-old rats were exposed continuously to 1764 $\mu g/m^3$ (0.9 ppm) of O_3 (Lunan et al., 1977). Ages of rats reported are presumably ages at initiation of exposure. In rats (10 to 40 days old) exposed for 3 days, G-6-PD activity was measured periodically during exposure. No statistical analyses were reported. Ozone caused a possible increase (20 percent of control) in the activity of G-6-PD in the 20-day-old group, and the magnitude continued to increase as age increased up to about 35 days (~ 75 percent of control), after which (40 and 50 days of age) the effect became less (40 percent of control at 50 days of age). In another experiment, a complex design was used in which rats at 10, 15, 25, and 32 days of age were exposed up to 32 to 34 days of age; thus, the duration of exposure for each group was different. When the animals were younger than 20 days, no effect was observed. When older mice were used, the greatest magnitude of the increased activity occurred at about 32 days of age, regardless of the absolute length of exposure.

Elsayed et al. (1982a) exposed rats of various ages to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 continuously for 92 hr. Ages given are those at initiation of exposure. Ozone increased lung weights, total lung protein, and total lung DNA in an age-dependent fashion, with the older (90-day-old) rats being more affected than 24-day-old animals. For isocitrate dehydrogenase activity, no effect was seen in the 24-day-old rats, but an increase was observed in the 90-day-old animals. For G-6-PD and 6-phosphogluconate dehydrogenase, increases were observed in the 24- and 90-day-old rats, with a greater magnitude of the effect occurring in the 90-day-old group. Younger rats (7 to 18 days old) were also examined. The exposure caused >60 percent mortality to the 7- and 12-day-old rats. Glucose-6-phosphate dehydrogenase activity decreased in both the 7-and-12-day old groups, with the younger rats being more affected. The 18-day-old rats had an increase in this activity. These trends were similar to those observed by Tyson et al. (1982), although the exact age for significant changes differed slightly.

The reason for these age-dependent changes is not known. The younger animals (< 24 days of age) have lower basal levels of the studied enzymes than the older animals examined (> 38 days of age) (Tyson et al., 1982; Elsayed et al., 1982a). It is conceivable that age influenced the dosimetry of O_3. The decreased activities observed in the neonates are reminiscent of the decreased activities that occur at higher O_3 levels in adults (DeLucia et al., 1972, 1975a; Fukase et al., 1975). The increased activities in the later stages of weanlings or in young, growing adults is consistent with the effects observed in other studies of adult rats (Table 10-5).

Mustafa et al. (1984) are the only researchers to report the effects of combined exposures to O_3 and nitrogen dioxide on the GSH peroxidase system. Mice were exposed 8 hr/day for 7 days to either 9024 $\mu g/m^3$ (4.8 ppm) of nitrogen dioxide, or 882 $\mu g/m^3$ (0.45 ppm) of O_3, or a mixture of these. Ozone and nitrogen dioxide alone caused no significant effects on most of the endpoints; however, synergistic effects were observed in the mixture group. The total sulfhydryl and nonprotein sulfhydryl contents were increased. The activities of GSH peroxidase, G-6-PD, 6-phosphogluconate dehydrogenase, and isocitrate dehydrogenase increased, but the activities of GSH reductase and GSH S-transferase were unchanged. Tissue O_2 utilization was also increased, as shown by the increase in succinate oxidate and cytochrome c oxidase activities.

Superoxide dismutase (SOD) catalyzes the dismutation of (and therefore destroys) superoxide (O_2-), a toxic oxidant species thought to be formed from O_3 exposure, and is thus involved in antioxidant metabolism. Rats exposed continuously for 7 days to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 exhibited an increased activity of SOD in cytosolic and mitochondrial fractions of the lungs (Mustafa et al., 1977). In a more complex exposure regimen in which rats were exposed for 3 days to 1568 $\mu g/m^3$ (0.8 ppm) and then various days of combinations of 2940 $\mu g/m^3$ (1.5 ppm) and 5880 $\mu g/m^3$ (3 ppm) of O_3, SOD activity also increased. Bhatnager et al. (1983) studied the time course of the increase in SOD activity after continuous exposure of rats to 882 $\mu g/m^3$ (0.45 ppm) of O_3. On day 2 of exposure, there was no effect. On days 3 and 5, activity had increased; by day 7 of exposure, values were not different from control.

10.3.3.3. Oxidative and Energy Metabolism. Mitochondrial enzyme activities are typically studied to evaluate effects on O_2 consumption, which is a fundamental parameter of cellular metabolism. Mitochondria are cellular organelles that are the major sites of O_2 utilization and energy production. Many of the enzymes in mitochondria have functional sulfhydryl groups, which are known to be affected by O_3, and mitochondrial membranes have unsaturated fatty acids that are also susceptible to O_3. The patterns of O_3 effects on O_2 consumption, as will be discussed, are quite similar to effects on antioxidant metabolism (Section 10.3.3.2).

Mustafa et al. (1973) showed in rats that acute (8-hr) exposure to a high concentration of O_3 (3920 $\mu g/m^3$, 2 ppm) decreases O_2 consumption using the substrates succinate, α-oxoglutarate, and glycerol-1-phosphate. Similar findings were made by DeLucia et al. (1975a). Decreases in mitochondrial total sulfhydryl levels were also observed (Mustafa et al., 1973). Equivalent changes occurred in whole-lung homogenate and the mitochondrial fraction. No change in malonaldehyde levels was found. When rats were exposed to high O_3 levels (5880 $\mu g/m^3$, 3 ppm; 4 hr), the immediate depression in succinate oxidase activity was followed by an increase that peaked about 2 days postexposure and returned to normal by 20 days postexposure (Mustafa et al., 1977). A 10- or 20-day continuous exposure to a lower O_3 concentration (1568 $\mu g/m^3$, 0.8 ppm) caused an increase in O_2 consumption of lung homogenate which was greater at 20 days (Mustafa et al., 1973). When the activity of the mitochondrial fraction per mg of protein was measured, the increased activity was less than that of the lung homogenate per mg of protein. Morphological comparisons indicated that the exposed lungs had a threefold increase in type 2 cells, which contain more mitochondria than type 1 cells. Thus, the increase in O_2 consumption appears to reflect changes in cell populations.

Schwartz et al. (1976) exposed rats for 7 days continuously or intermittently (8 hr/day) to 392, 980, or 1568 $\mu g/m^3$ (0.2, 0.5, or 0.8 ppm) of O_3. Succinate oxidase activity increased linearly with O_3 concentration. No major differences were apparent between continuous and intermittent exposures. No statistical analyses were reported. Concentration-dependent morphological effects were also observed (Section 10.3.1). When using rats and an identical exposure regimen, Mustafa and Lee (1976) found similar responses for succinate oxidase and succinate-cytochrome c reductase activity. These increases were statistically significant. Mustafa et al. (1973), when using 7 days of continuous exposure, also showed that O_2 consumption of rats increased with increasing O_3 level (392, 980, 1568 $\mu g/m^3$, 0.2, 0.5, 0.8 ppm).

Although concentration appears to be a stronger determinant of the effect, time of exposure also plays a role (Mustafa and Lee, 1976). Rats were exposed to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 continuously for 30 days, and O_2 consumption was measured as the activities of succinate oxidase, 2-oxoglutarate oxidase, and glycerol-1-phosphate oxidase. On day 1, the effect was not significant. However, at day 2 and following, these enzyme activities increased. The peak increase occurred on day 4 and remained at that elevated level throughout the

30 days of exposure. Mitochondrial succinate-cytochrome c reductase exhibited a similar pattern under similar O_3 levels for 7 days of exposure. Equivalent results occurred in rats during a 7-day continuous exposure to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 (DeLucia et al., 1975a).

In rats, recovery from an ozone-induced (1568 $\mu g/m^3$, 0.8 ppm; 3 days, continuous) increase in succinate oxidase activity occurred by 6 days post-exposure (Chow et al., 1976b). When the rats were re-exposed to the same exposure regimen at 6, 13, and 27 days of recovery, the increased activity was equivalent to that of the initial exposure. Thus, no long-lasting tolerance was observed.

Dietary vitamin E can also reduce the effects of O_3 on O_2 consumption. After 7 days of continuous exposure to 196 or 392 $\mu g/m^3$ (0.1 or 0.2 ppm) of O_3, the lung homogenates of rats maintained on diets with either 11 or 66 ppm of vitamin E were examined for changes in O_2 consumption (succinate oxidase activity) (Mustafa, 1975; Mustafa and Lee, 1976). In the 11-ppm vitamin E group, increases in O_2 consumption occurred at both O_3 levels. In the 66-ppm vitamin E group, only 392 $\mu g/m^3$ (0.2 ppm) of O_3 caused an increase. Mitochondria were isolated from the lungs and studied. Neither dietary group had O_3-induced changes in the respiratory rate of mitochondria (on a per mg of protein basis). However, the amount of mitochondria (measured as total protein content of the mitochondrial fraction of the lung) from the O_3-exposed rats of the 11-ppm vitamin E group did increase (15-20 percent).

Similar to earlier discussions for antioxidant metabolism (Section 10.3.3.2), responsiveness to effects of O_3 on O_2 consumption is age-related (Table 10-5). Elsayed et al. (1982a) exposed rats of various ages to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 continuously for 92 hr. The O_3-induced increase in the activities of succinate oxidase and cytochrome c oxidase increased with age (from 24 to 90 days of age), with no significant change at 24 days of age. When younger rats were examined, succinate oxidase activity decreased in both the 7- and 12-day-old animals, with the younger ones more affected. The 18-day-old rats had an increase in this activity.

Species and strain differences were observed after a 5-day continuous exposure to 882 $\mu g/m^3$ (0.45 ppm) of O_3 (Mustafa et al., 1982). Mice and Sprague Dawley rats (but not other strains of rats) had an increase in activity of succinate oxidase. Cytochrome c oxidase was increased in mice, Long-Evans rats, and Sprague Dawley rats, but not Wistar rats; the increase in the mice was greater than that in the rats.

Rats have also been compared to two strains of monkeys after a 7-day (8 hr/day) exposure to various concentrations of O_3 (Mustafa and Lee, 1976). Rats were exposed to 392, 980, or 1568 $\mu g/m^3$ (0.2, 0.5, or 0.8 ppm) of O_3 and exhibited increases in succinate oxidase activity. Rhesus monkeys exposed to either 980 or 1568 $\mu g/m^3$ (0.5 or 0.8 ppm) of O_3 had an increase in this enzyme activity only at the higher exposure concentration. When Bonnet monkeys were exposed to 392, 686, or 980 $\mu g/m^3$ (0.2, 0.35, or 0.5 ppm) of O_3, succinate oxidase activity increased at the two higher O_3 levels. The number of animals used was not specified, which makes interpretation difficult. At the 392-$\mu g/m^3$ (0.2 ppm) level, the increase in rats was to 118 percent of controls (significant); in Bonnet monkeys, it was to 113 percent of controls (not significant). At the 980-$\mu g/m^3$ (0.5 ppm) of O_3 level, the magnitude of the significant increases was not different between rats (133 percent of controls) and Bonnet monkeys (130 percent of controls). Rhesus monkeys may have been slightly less responsive than rats, but no statistical analyses were performed to assess this question.

The increase in levels of nonprotein sulfhydryls, antioxidant enzymes, and enzymes involved in O_2 consumption is typically attributed to concurrent morphological changes (Section 10.3.1) in the lungs, principally the loss of type 1 cells and the increase of type 2 cells and the infiltration of alveolar macrophages. Several investigators have made such correlated observations in rats (Plopper et al., 1979; Chow, et al., 1981; Schwartz et al., 1976; DeLucia et al., 1975a). Type 2 cells are more metabolically active than type 1 cells and have more abundant mitochondria and endoplasmic reticula. This hypothesis is supported by the findings of Mustafa et al. (1973), Mustafa (1975), and DeLucia et al. (1975a). For example, succinate oxidase was studied in both lung homogenates and isolated mitochondria of rats after a 7-day exposure to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 (DeLucia et al., 1975a). The increase in the homogenate was about double that of the isolated mitochondria (on a per mg of protein basis). As mentioned previously, this indicates that an increase in the number of mitochondria, rather than an increased activity within a given mitochondrion, in exposed lungs is the probable dominant cause.

10.3.3.4 Monooxygenases. Multiple microsomal enzymes function in the metabolism of both endogenous (e.g., biogenic amines, hormones) and exogenous (xenobiotic) substances. These substrates are either activated or detoxified, depending on the substrate and the enzyme. Only a few of the enzymes have been studied subsequent to O_3 exposure (Table 10-6).

TABLE 10-6. MONOOXYGENASES

Ozone concentration μg/m³	ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
392 980 1568	0.2 0.5 0.8	MAST NBKI	Continuous or 8 hr/day for 7 days	Concentration-related linear increase in NADPH cytochrome c reductase activity. No difference between continuous and intermittent.	Rat	Mustafa and Lee, 1976; Schwartz et al., 1976; Mustafa et al., 1977
1470 5880 19,600	0.75 3.0 10.0	I	3 hr	Decreased activity of benzpyrene hydroxylase in lung parenchyma.	Hamster	Palmer et al., 1971
1470 5880 19,600	0.75 3.0 10.0	I	3 hr	Decreased activity of benzpyrene hydroxylase in tracheobronchial mucosae.	Rabbit	Palmer et al., 1972
1568	0.8	ND	Continuous for 7 days	High O_3 level reduced monoamine oxidase activity; low O_3 level increased it.	Rat	Mustafa et al., 1977
3920	2.0		8 hr			
1568	0.8	I	Continuous for 7 days	High O_3 level decreased activity of NADPH cytochrome c reductase; low level increased it.	Rat	DeLucia et al., 1972, 1975a
3920	2.0		8 hr			
392 1568 1568	0.2 0.5 0.8	I	Continuous or 8 hr/day	Increased activity of NADPH cytochrome c reductase. At 0.8 ppm, increase began at day 2 of exposure.	Rat	DeLucia et al., 1975a
1568	0.8		8 hr/day	No change in NADPH cytochrome c reductase activity.	Monkey	
1568	0.8	I	Continuous for 7 days	Increased activity of NADPH cytochrome c reductase on days 2 through 7. Maximal increase on day 4.	Rat	Mustafa and Lee, 1976

TABLE 10-6. MONOOXYGENASES (continued)

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
μg/m³	ppm					
1960	1.0	ND	90 min	Decreased levels of lung cytochrome P-450. Maximal decrease at 3.6 days postexposure.	Rabbit	Goldstein et al., 1975
1960	1.0	MAST	24 hr	50% decrease in benzphetamine N-demethylase activity 1 day postexposure; return to control levels by 1 wk postexposure. Stimulation of cytochrome b_5-mediated lipid desaturation.	Rat	Montgomery and Niewoehner, 1979
5880	3	NBKI	10 min before lung perfusion and continuous throughout experiment.	Decreased enzymatic conversion of arachidonic acid to prostaglandins when using isolated ventilated perfused lung.	Rat	Menzel et al., 1976

[a]Measurement method: MAST = KI-coulometric (Mast meter); CHEM = gas solid chemiluminescence; NBKI = neutral buffered potassium iodide; I = Iodometric; ND = not described.

[b]Calibration method: UKI = unbuffered potassium iodide.

Monoamine oxidase (MAO) activity has been investigated (Mustafa et al., 1977) in view of its importance in catalyzing the metabolic degradation of bioactive amines like 5-hydroxytryptamine and norepinephrine. Although MAO activity is located principally in the mitochondria, it also is found in microsomes. Activity levels of MAO in rats were determined after exposure to 3920 $\mu g/m^3$ (2 ppm) for 8 hr or 1568 $\mu g/m^3$ (0.8 ppm) continuously for 7 days. Substrates used included n-amylamine, benzylamine, tyramine, and 3-hydroxytyramine; three tissue preparations were used (whole lung homogenate, mitochondria, and microsomes). The acute high-level exposure reduced MAO activity in all tissue preparations. The longer exposure to 1568 $\mu g/m^3$ (0.8 ppm) increased MAO activity in all tissue preparations. This pattern is similar to that found for mitochondrial enzymes and antioxidant metabolism (Sections 10.3.3.2 and 10.3.3.3).

The cytochrome P-450-dependent enzymes have been studied because of their function in drug and carcinogen metabolism. Palmer et al. (1971, 1972) found that hamsters exposed to 1,470 $\mu g/m^3$ (0.75 ppm) of O_3 for 3 hr had lower benzo(a)pyrene hydroxylase activity. Goldstein et al. (1975) showed that rabbits exposed to 1,960 $\mu g/m^3$ (1 ppm) of O_3 for 90 min had decreased levels of lung cytochrome P-450. Maximal decreases occurred 3.6 days following exposure. Recovery to control values occurred somewhere between 8 days and 45 days. Cytochrome P-450-mediated activity of benzphetamine N-demethylase in the lung was lowered by a 24-hr exposure to 1,960 $\mu g/m^3$ (1 ppm) of O_3 in rats (Montgomery and Niewoehner, 1979). The cytochrome P-450 dependent activity began to recover by 4 days postexposure but was still decreased. Complete recovery occurred by 1 week. Cytochrome b_5-mediated lipid desaturation was stimulated by O_3 4, 7, and 14 days postexposure. Immediately after exposure, the desaturase activity was quite depressed, but this was attributed to anorexia in the rats, and not to O_3. Cytochrome P-450-dependent enzymes exist in multiple forms, because they have different substrate affinities that overlap. Measuring activity with only one substrate does not characterize a single enzyme. More importantly, the relatively long time for recovery suggests that cell injury, rather than enzyme destruction, has occurred. Benzo(a)pyrene hydroxylase is the first major enzyme in the activation of benzo(a)pyrene and several other polycyclic hydrocarbons to an active carcinogen. However, additional enzymes not studied after O_3 exposure are involved in the activation, which makes full interpretation of the effect of O_3 on this metabolism impossible. The impact of the decrease in cytochrome P-450 depends on the activation or detoxification of the metabolized compound by this system.

Also involved in mixed function oxidase metabolism is NADPH cytochrome c reductase. As with other classes of enzymes (Sections 10.3.3.2; 10.3.3.3), acute exposure to a high O_3 level (3920 µg/m^3, 2 ppm; 8 hr) reduced NADPH cytochrome c reductase activity (DeLucia et al., 1972, 1975a). After a continuous or 8 hr/day exposure of rats for 7 days, the activity of NADPH cytochrome c reductase increased linearly in a concentration-related fashion (392, 980, and 1568 µg/m^3; 0.2, 0.5, and 0.8 ppm) (Mustafa and Lee, 1976; Schwartz et al., 1976; Mustafa et al., 1977). Continuous and intermittent exposures were not different. The time course of the response to 1568 µg/m^3 (0.8 ppm) was an increase in activity that began at day 2, peaked at day 4, and was still increased at day 7 of continuous exposure in the rat (Mustafa and Lee, 1976). The rat, but not the Rhesus monkey, is apparently affected after exposure for 8 hr/day for 7 days to 1568 µg/m^3 (0.8 ppm) of O_3 (DeLucia et al., 1975a). However, monkey data were not reported in any detail.

10.3.3.5 Lactate Dehydrogenase and Lysosomal Enzymes. Lactate dehydrogenase (LDH) and lysosomal enzymes are frequently used as markers of cellular damage if levels are observed to increase in lung lavage or serum/plasma, because these enzymes are released by cells upon certain types of damage. Effects of O_3 on these enzymes are described on Table 10-7. No lung lavage studies have been reported; whole-lung homogenates were used. Therefore, it is not possible to determine whether the observed increases reflect a leakage into lung fluids and a compensatory resynthesis in tissue or cellular changes (See Section 10.3.1), such an increase in type 2 cells and alveolar macrophages and polymorphonuclear leukocytes rich in lysosomal hydrolases. In some instances, correlation with plasma values was sought. They are described briefly here, more detail is given in Section 10.4.3.

Lactate dehydrogenase is an intracellular enzyme that consists of two subunits combined as a tetramer. Various combinations of the two basic subunits change the electrophoretic pattern of LDH so that its various isoenzymes can be detected. Chow and Tappel (1973) found an increase in LDH activity in the homogenate of rat lungs exposed to 1568 µg/m^3 (0.8 ppm) of O_3 continuously for 7 days. Lower levels (196 µg/m^3, 0.1 ppm; 7 days continuous) only increased LDH activity of lung homogenate when rats were on a diet deficient in vitamin E (Chow et al., 1981). Vitamin E levels in the diet did not significantly influence the response. In following up this finding, Chow et al. (1977) studied

TABLE 10-7. LACTATE DEHYDROGENASE AND LYSOSOMAL ENZYMES

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
μg/m³	ppm					
196	0.1	NBKI	Continuous for 7 days	Increase in total LDH activity in diet group receiving 0 ppm vitamin E. Groups with 11 or 110 ppm of vitamin E had no effect.	Rat	Chow et al., 1981
392 980 1568	0.2 0.5 0.8	MAST, NBKI	Continuous for 8 days or 8 hr/days for 7 days	Increased lung lysozyme activity only after continuous exposure to 0.8 ppm.	Rat	Chow et al., 1974
980 1568	0.5 0.8	NBKI	8 hr/day for 7 days	Increased LDH activity in lungs. Change in LDH isoenzyme distribution at 0.8 ppm.	Rat	Chow et al., 1977
1568	0.8			No change in total LDH activity or isoenzyme pattern in lungs.	Monkey	
1372	0.7	NBKI	Continuous for 5 days	Specific activities of various lysosomal hydrolases increased.	Rat	Dillard et al., 1972
1568	0.8		Continuous for 7 days			
1372- 1568	0.7- 0.8	MAST, NBKI	Continuous for 7 days	Increase in lung acid phosphatase activity; no observed increases in B-glucuronidase activity.	Rat	Castleman et al., 1973a
1568	0.8	MAST, NBKI	Continuous for 7 days	Bronchiolar epithelium had decreased NADH and NADPH activities and increased ATPase activity.	Rat	Castleman et al., 1973b
1568	0.8	MAST, NBKI	Continuous for 7 days	Increase in LDH activity not affected by vitamin E (0 or 45 mg/kg diet).	Rat	Chow and Tappel, 1973

[a] Measurement method: MAST = KI-coulometric (Mast meter); NBKI = neutral buffered potassium iodide.

[b] Calibration method: NBKI = neutral buffered potassium iodide.

LDH activity and isoenzyme pattern (relative ratios of different LDH isoenzymes) in the lungs, plasma, and erythrocytes of O_3-exposed rats (980 or 1,568 $\mu g/m^3$, 0.5 or 0.8 ppm) and monkeys (1568 $\mu g/m^3$, 0.8 ppm). Exposure was for 8 hr/day for 7 days. In monkeys, no significant changes in either total LDH activity or isoenzyme pattern in lungs, plasma, or erythrocytes were detected. The total LDH activity in the lungs of rats was increased after exposure to 1,568 or 980 $\mu g/m^3$ (0.8 or 0.5 ppm), but no changes in the plasma or erythrocytes were detected. The isoenzyme pattern of LDH following O_3 exposure was more complex, with the LDH-5 fraction significantly decreased in lungs and plasma of rats exposed to 1,568 $\mu g/m^3$ (0.8 ppm). The LDH-4 fraction in lungs and plasma and the LDH-3 fraction in lungs were increased. No changes were discernible in rats exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3. The changes in LDH isoenzyme pattern appeared to be due to a relative increase in the LDH isoenzymes containing the H (heart type) subunits. Although the increase in LDH suggests cytotoxicity after O_3 exposure, no clear-cut interpretation can be placed on the importance of the isoenzyme pattern. Some specific cell types in the lung may contain more H-type LDH than others and be damaged by O_3 exposure. Further studies of the fundamental distribution of LDH in lung cell types are needed to clarify this point.

Lysosomal enzymes have been found to increase in the lungs of animals exposed to O_3 at concentrations of 1,372 ± 294 $\mu g/m^3$ (0.70 ± 0.15 ppm) for 5 days and 1,548 ± 274 $\mu g/m^3$ (0.79 ± 0.14 ppm) for 7 days, whether detected by biochemical (whole-lung homogenates and fractions) or histochemical means (Dillard et al., 1972). Dietary vitamin E (0 to 1500 mg/kg diet) did not influence the effects. These increased activities were attributed to the infiltration of the lung by phagocytic cells during the inflammatory response phase from O_3 exposure. Similarly, Castleman et al. (1973a,b) found that activity of lung acid phosphatase was increased in young rats that had been exposed to 1,372 to 1,568 $\mu g/m^3$ (0.7 to 0.8 ppm) of O_3 continuously for 7 days. Increases in β-glucuronidase activity were not observed. The histochemical and cytochemical localization suggested that O_3 exposure results in damage to the lung's lysosomal membranes. Castleman et al. (1973b) also found that the bronchiolar epithelium in infiltrated areas had lower NADPH- and NADH diaphorase activities and higher ATPase activities than similar epithelium of control lungs. They discussed in greater detail the enzymatic distribution within the lung and suggested that some of the pyridine nucleotide-dependent reactions could represent an enzymatic protective mechanism operating locally in the centriacinar regions of O_3-exposed lungs. Chow et al. (1974) also observed an increase in lysozyme activity (lung homogenate) in rats exposed continuously to 1568 $\mu g/m^3$ (0.8 ppm) for 8 days but not in rats exposed intermittently (8 hr/day, 7 days). No effect was seen in continuous or intermittent exposure of rats to 392 or 980 $\mu g/m^3$ (0.2 or 0.5 ppm) of O_3.

Lysosomal acid hydrolases include enzymes that digest protein and can initiate emphysema. The contribution of the increases in these enzymes observed by some after O_3 exposure to morphological changes has not been demonstrated.

10.3.3.6 Protein Synthesis. The effects of O_3 on protein synthesis can be divided into two general areas: (1) the effects on the synthesis of collagen and related structural connective tissue proteins, and (2) the effects on the synthesis or secretion of mucus. The studies are summarized in Table 10-8.

Hesterberg and Last (1981) found that increased collagen synthesis caused by continuous exposure to O_3 at 1568, 2352, and 2940 $\mu g/m^3$ (0.8, 1.2, and 1.5 ppm) for 7 days could be inhibited by concurrent treatment with methylprednisolone (1 to 50 mg/kg/day).

Hussain et al. (1976a,b) showed that lung prolyl hydroxylase activity and hydroxyproline content increased on exposure of rats to 980 and 1568 $\mu g/m^3$ (0.5 and 0.8 ppm) of O_3 for 7 days. At 392 $\mu g/m^3$ (0.2 ppm), O_3 produced a statistically insignificant increase in prolyl hydroxylase activity. Prolyl hydroxylase is the enzyme that catalyzes the conversion of proline to hydroxyproline in collagen. This conversion is essential for collagen to form the fibrous conformation necessary for its structural function. Hydroxyproline is an indirect measure of collagen content. When rats were exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3 for 30 days, the augmentation of activity seen earlier at 7 days of exposure had diminished, and by 60 days, the enzyme activity was within the normal range despite continued O_3 exposure. When rats were exposed to 1568 $\mu g/m^3$ (0.8 ppm) of O_3, the prolyl hydroxylase activity continued to rise for about 7 days; hydroxyproline content of the lung rose to a maximum value at about 3 days after exposure began and remained equivalently elevated through day 7 of exposure. Incorporation of radiolabeled amino acids into collagen and noncollagenous protein rose to a plateau value at about 3 (collagenous) or 4 to 7 (noncollagenous) days after exposure. Synthesis of collagen was about 1.6 times greater than that of noncollagenous proteins during the

TABLE 10-8. EFFECTS OF OZONE ON LUNG PROTEIN SYNTHESIS

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
μg/m³	ppm					
392 784 1176	0.2 0.4 0.6	ND	8 hr/day for 3 days	Decreased rate of glycoprotein secretion by tracheal explants at 0.6 ppm.	Rat	Last and Kaizu, 1980; Last and Cross, 1978
1568	0.8		Continuous for 1 through 90 days	Decreased rate of glycoprotein secretion.		
980	0.5		Continuous for 3 or 14 days and combined with H_2SO_4	Increased rate of glycoprotein secretion.		
392 980 1568	0.2 0.5 0.8	MAST	Continuous for 7 days	Concentration-dependent increase in lung prolyl hydroxylase activity. No effect at 0.2 ppm. Metabolic adaptation suggested at 980 μg/m³ (0.5 ppm) At 0.8 ppm, collagen and noncollagenous protein synthesis increased; effect on proylhydroxylase returned to normal by about 10 days postexposure, but hydroxyproline was still increased at 28 days.	Rat	Hussain et al., 1976a,b
392 784 1176 1568	0.2 0.4 0.6 0.8	UV	8 hr/day for 1 to 90 days	At 0.8 ppm, tracheal explants had decreased rate of glycoprotein secretion for up to 1 wk, followed by increased rate up to 12 wks. Three day exposure to three lower concentrations caused decrease at only 0.6 ppm.	Rat	Last et al., 1977
392 1568 3920	0.2 0.8 2.0	UV, NBKI	6 hr/day, 5 days/wk, 12.4 wk (62 days of exposure)	Decrease in collagen and elastin at 0.2 and and 0.8 ppm; increase at 2 ppm.	Rat	Costa et al., 1983
980- 3920	0.5- 2	UV	1, 2, or 3 wk	Increased rate of collagen synthesis; fibrosis of alveolar duct walls; linear concencentration response.	Rat	Last et al., 1979

TABLE 10-8. EFFECTS OF OZONE ON LUNG PROTEIN SYNTHESIS (continued)

Ozone concentration µg/m³	Ozone concentration ppm	Measurement method[a,b]	Exposure duration and protocol	Observed effect(s)	Species	Reference
882	0.45	ND	Continuous for 7 days	Increased collagen synthesis at 5 and 7, but not 2 days of exposure. Similar pattern for increase in superoxide dismutase activity. Increased prolyl hydroxylase activity at 2, 3, 5, and 7 days of exposure; maximal effect at day 5.	Mouse	Bhatnagar et al., 1983
1568	0.8	ND	Continuous for 90 days	Increase in prolyl hydroxylase activity through 7 days. No effect 20 days and beyond.	Rat	
980	0.5	UV	Continuous for up to 180 days	Increase in protein and hydroxyproline content of lungs. No change 2 mo postexposure.	Rat	Last and Greenberg, 1980
1568	0.8	ND	Continuous for 7 days	Decreased protein synthesis on day 1; increased synthesis day 2 and thereafter; peak response on days 3 and 4.	Rat	Mustafa et al., 1977
1568	0.8	NBKI	Continuous for 3 days	Increased protein synthesis; recovery by 6 days later; after re-exposure 6, 13, or 27 days later, protein synthesis increased.	Rat	Chow et al., 1976b
1568 2352 2940	0.8 1.2 1.5	UV	Continuous for 7 days	Net rate of collagen synthesis by lung minces increased in concentration-dependent manner; methyl prednisolone administered during O_3 exposure prevented increase.	Rat	Hesterberg and Last, 1981

[a] Measurement method: MAST = KI-coulometric (Mast meter); UV = UV photometry; NBKI = neutral buffered potassium iodide; ND = not described.

[b] Calibration method: NBKI = neutral buffered potassium iodide.

first few days of exposure; no major differences were apparent by 7 days of exposure. After the 7-day exposure ended, about 10 days were required for recovery to initial values of prolyl hydroxylase. However, hydroxyproline levels were still increased 28 days postexposure. This suggests that although collagen biosynthesis returns to normal, the product of that increased synthesis, collagen, remains stable for some time.

The shape of the concentration response curve was investigated by Last et al. (1979) for biochemical and histological responses of rat lungs after exposure to ozone for 1, 2, or 3 weeks at levels ranging from 980 to 3920 µg/m^3 (0.5 to 2 ppm). A general correlation was found between fibrosis detected histologically and the quantitative changes in collagen synthesis in minces of O_3-exposed rat lungs. The stimulation of collagen biosynthesis was essentially the same, regardless of whether the rats had been exposed for 1, 2 or 3 weeks; it was linearly related to the O_3 concentration to which the rats were exposed.

Continuous exposure of mice for 7 days to 882 µg/m^3 (0.45 ppm) of O_3 caused an increase in collagen synthesis after 5 or 7, but not 2 days of exposure (Bhatnagar et al., 1983). The 5- and 7-day results showed little if any difference. The effect on synthesis of noncollagen protein was not significant. Prolyl hydroxylase activity was also increased at 2, 3, 5, and 7 days of exposure, with the maximal increase at day 5. The day 7 results were only slightly different (no statistical analysis) from the day 2 data. Superoxide dismutase activity was investigated, because it has been observed (in other studies) to prevent a superoxide-induced increase in collagen synthesis and prolyl hydroxylase. Activity of superoxide dismutase increased in a pattern parallel to that for collagen synthesis.

Bhatnagar et al. (1983) also studied rats exposed continuously for 90 days to 1568 µg/m^3 (0.8 ppm) of O_3. Prolyl hydroxylase activity continued to increase through 7 days of exposure. By 20, 50, and 90 days of exposure, no significant effects were observed.

Effects of subchronic O_3 exposure have been studied by Last and Greenberg (1980). Rats were exposed to 980 µg/m^3 (0.5 ppm) continuously for up to 180 days and examined at various times during exposure and 2 months after exposure ceased. The total protein content of the lungs increased during exposure, with the greatest increase after 88 days of exposure. By 53 days postexposure, values had returned to control levels. Hydroxyproline content of the lungs also increased following 3, 30, 50, or 88, but not 180, days of exposure. No such effect was observed at the 53-day postexposure examination. The rates of protein and hydroxyproline synthesis were also measured. Protein synthesis was not affected significantly. Although the authors mentioned that hydroxyproline synthesis rates "appeared to be greater", statistical significance was not discussed and values appeared to be only slightly increased, considering the variability of the data. In discussing their data, the authors referred to a concurrent morphological study (Moore and Schwartz, 1981) that showed an increase in lung volume, mild thickening of the interalveolar septa and alveolar interstitium, and an increase in collagen (histochemistry) in these areas. Different results for collagen levels were observed after another longer term exposure (6 hr/day, 5 days/wk, 12.4 wk) to 392, 1568, or 3920 $\mu g/m^3$ (0.2, 0.8, or 2.0 ppm) of O_3 (Costa et al., 1983). At the two lower concentrations, rats exhibited an equivalent decrease in hydroxyproline. At the highest concentration, an increase was observed. Similar findings were made for elastin levels.

Protein synthesis (incorporation of radiolabeled leucine) was increased in rats after 3 days of continuous exposure to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 (Chow et al., 1976b). Recovery had occurred by 6 days postexposure. No adaptation was observed, because when animals were re-exposed to the same O_3 regimen 6, 13 or 27 days after the first exposure, protein synthesis increased as it had earlier. Mustafa et al. (1977) investigated the time course of the increased in vivo incorporation of radioactive amino acids. Rats were exposed continuously for 7 days to 1568 $\mu g/m^3$ (0.8 ppm) of O_3. No statistics were reported. One day of exposure caused a decrease in protein synthesis. However, by day 2, an increase occurred, which peaked on days 3 and 4 of exposure. On day 7, the effect had not diminished. The authors attributed this finding to synthesis of noncollagenous protein. They also found no radioactive incorporation into blood or alveolar macrophages. Hence, the observed increases were due to lung tissue protein synthesis, and not a concurrent influx of alveolar macrophages or serum into the lungs.

The production of mucus glycoproteins and their secretion by tracheal explants have been reviewed by Last and Kaizu (1980). Mucus glycoprotein synthesis and secretion were measured by the rate of incorporation of ^{3}H-glucosamine into mucus glycoproteins and their subsequent secretion into supernatant fluid of the tracheal explant culture medium. This method has been found to be a reproducible index of mucus production, and these authors maintain that this measurement ex vivo following exposure in vivo is representative of injuries occurring in vivo. When rats were exposed to 1568 µg/m^3 (0.8 ppm) of O_3 for 8 hr/day for 1 to 90 days, Last et al. (1977) found a depression of glycoprotein synthesis and secretion into the tissue culture medium for the initial week that was statistically significant only on days 1 and 2 of exposure. Rebound occurred subsequently, with increased glycoprotein secretion for at least 12 weeks of continued exposure to O_3 (only significant at 1 and 3 months of exposure). Rats were also exposed intermittently for 3 days to 1176, 784, and 392 µg/m^3 (0.6, 0.4, 0.2 ppm) of O_3. Glycoprotein secretion decreased only at the higher concentration. Tracheal explants from Bonnet monkeys exposed to 0, 980, or 1568 µg/m^3 (0, 0.5 or 0.8 ppm) O_3 for 7 days appeared to have increased rates of secretion of mucus (Last and Kaizu, 1980). However, few monkeys were used and statistical analysis was not reported.

A combination exposure to O_3 (980 µg/m^3; 0.5 ppm) and sulfuric acid (H_2SO_4) aerosol (1.1 mg/m^3) caused complex effects on mucus secretions in rats (Last and Kaizu, 1980; Last and Cross, 1978). A 3-day exposure to 980 µg/m^3 (0.5 ppm) of O_3 decreased mucus secretion rates, but H_2SO_4 had no effect. In rats exposed to the combination of H_2SO_4 aerosol and O_3, mucus secretion significantly increased. After 14 days of continuous exposure, the rats receiving a combined exposure to both H_2SO_4 aerosol and O_3 had elevated values (132 percent) over the control group of animals. Because mucus secretion and synthesis are intimately involved in diminishing the exposure of underlying cells to O_3 and removing adventitiously inhaled particles, alterations in the mucus secretory rate may have significant biological importance. Experiments reported to date do not clearly indicate what human health effects may be likely, nor their importance.

10.3.3.7 Lipid Metabolism and Content of the Lung. If O_3 initiates peroxidation of unsaturated fatty acids in the lung, then changes in the fatty acid composition of the lung indicative of this process should be detectable. Because the fatty acid content of the lung depends on the dietary intake, changes in fatty acid content due to O_3 exposure are difficult to determine in the absence of rigid dietary control. Studies on lipid metabolism and content of the lung are summarized in Table 10-9. Generally, the unsaturated fatty acid content decreased in rats exposed to 980 µg/m^3 (0.5 ppm) of O_3 for up to 6 weeks (Roehm et al., 1972).

TABLE 10-9. EFFECTS OF OZONE EXPOSURE ON LIPID METABOLISM AND CONTENT OF THE LUNG

Ozone concentration µg/m³	ppm	Measurement[a] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
980	0.5	I	Continuous for 2, 4, or 6 wk	Increase in arachidonic and palmitic acids; decrease in oleic and linoleic acids.	Rat	Roehm et al., 1972
980 1568	0.5 0.8	UV	8 hr/day for 7, 28, or 90 days	No effect on ethane and pentane production in animals fed diets supplemented with high levels of vitamin E.	Monkey	Dumelin et al., 1978a
1960	1.0	NBKI	60 min	With vitamin E-deficient diet, increased pentane production and decreased ethane production. With vitamin E supplementation of 11 or 40 IU vitamin E/kg diet, decreased ethane and pentane production.	Rat	Dumelin et al., 1978b
1960	1.0	ND	4 hr	Decreased incorporation of fatty acids into lecithin.	Rabbit	Kyei-Aboagye et al., 1973

[a]Measurement method: NBKI = neutral buffered potassium iodide; UV = UV photometry; I = iodometric; ND = not described.

Peroxidation of polyunsaturated fatty acids produces pentane and ethane to be exhaled in the breath of animals (Donovan and Menzel, 1978; Downey et al., 1978). A discussion of the use of ethane and pentane as indicators of peroxidation is presented by Gelmont et al. (1981) and Filser et al. (1983). Normal animals and humans exhale both pentane and ethane in the breath. Dumelin et al. (1978b) found that exhalation of ethane decreased and exhalation of pentane increased when rats were deficient in vitamin E and exposed to 1960 μg/m^3 (1 ppm) of O_3 for 60 min. The provision of 11 (minimum vitamin requirement) or 40 IU (supplemented level) of vitamin E acetate per kg of diet resulted in a decrease in expired ethane and pentane after O_3 exposure. Dumelin et al. (1978a) also measured breath ethane and pentane in Bonnet monkeys exposed to 0, 980, or 1568 μg/m^3 (0, 0.5, or 0.8 ppm) of O_3 for 7, 28, or 90 days. They failed to detect any additional ethane or pentane in the breath of these monkeys and attributed the lack of such additional evolution to be due to the high level of vitamin E provided in the food.

Kyei-Aboagye et al. (1973) found that the synthesis of lung surfactant in rabbits, as measured by dipalmitoyl lecithin synthesis, was inhibited by exposure to 1960 μg/m^3 (1 ppm) of O_3 for 4 hr. Pulmonary lavage showed an increase in radiolabeled lecithins. The authors proposed that O_3 may decrease lecithin formation while simultaneously stimulating the release of surfactant lecithins. This may suggest the presence of a larger disarrangement of lipid metabolism following O_3 exposure. However, although changes in lipid composition of lavage fluid occur, the changes apparently do not alter the surface tension lowering properties of the fluid, as shown by Gardner et al. (1971) and Huber et al. (1971) when using high levels of O_3 ($\geq$ 9800 μg/m^3; 5 ppm).

10.3.3.8 Lung Permeability. Table 10-10 summarizes studies of the effects on lung permeability of exposures to different concentrations of O_3.

The lung possesses several active-transport mechanisms for removal of substances from the airways to the capillary circulation. These removal mechanisms have been demonstrated to be carrier-mediated and specific for certain ions. Williams et al. (1980) studied the effect of O_3 on active transport of phenol red in the lungs of rats exposed to 1176 to 4116 μg/m^3 (0.6 to 2.1 ppm) of O_3 continuously for 24 hr. Ozone inhibited the carrier-mediated transport of intratracheally instilled phenol red from the lung to the circulation and

TABLE 10-10. EFFECTS OF OZONE ON LUNG PERMEABILITY

Ozone concentration µg/m³	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
196 510 1000 1960	0.1 0.26 0.51 1.0	CHEM, UV	3 hr or 72 hr	Increased levels of lavage fluid protein ≥ 0.26 ppm immediately after 72-hr exposure or 15 hr after a 3-hr exposure. Vitamin C deficiency did not influence sensitivity.	Guinea pig	Hu et al., 1982
353	0.18		3 hr; 8 hr/day for 5 or 10 days	No effect on protein levels.		
510 980	0.26 0.5		3, 24, or 72 hr	Lavage was 15 hr postexposure. At 0.26 ppm increased protein only after 24 hr exposure; at 0.5 ppm, increased protein after 24 hr of exposure.		
1000	0.51		3 hr	Increase in protein levels at 10- and 15-(but not 0, 5, or 24) hr postexposure.		
490 980 1960 4900	0.25 0.5 1.0 2.5	MAST, NBKI	6 hr	Increased alveolar protein accumulation at 0.5 ppm and above.	Rat	Alpert et al., 1971a
1176 2156 3136 4116	0.6 1.1 1.6 2.1	NBKI	24 hr	Concentration-dependent loss of carrier-mediated transport for phenol red.	Rat	Williams et al., 1980
1960- 2940	1.0- 1.5	MAST	2 hr	Increased albumin and immunoglobin G in airway secretions.	Dog	Reasor et al., 1979

[a] Measurement method: MAST = KI-coulometric (Mast meter); CHEM = gas phase chemiluminescence; UV = UV photometry; NBKI = neutral buffered potassium iodide.

[b] Calibration method: NBKI = neutral buffered potassium iodide; UV = UV photometry.

increased the nonspecific diffusion of phenol red from the lung. These changes in ion permeability may also explain in part the effects of O_3 on the respiratory response of animals to bronchoconstrictors (Lee et al., 1977; Abraham et al., 1980).

As another index of increased lung permeability following O_3 exposure, the appearance of albumin and immunoglobins in airway secretions has been examined. Reasor et al. (1979) found that dogs breathing 1960 to 2940 $\mu g/m^3$ (1.0 to 1.5 ppm) of O_3 had increased albumin and immunoglobin G content of their airway secretions. Alpert et al. (1971a), using rats exposed for 6 hr to 490 to 4900 $\mu g/m^3$ (0.25 to 2.5 ppm) O_3, also found increased albumin in lung lavage in animals exposed to 980 $\mu g/m^3$ (0.5 ppm) or more.

In a series of experiments, Hu et al. (1982) exposed guinea pigs to 196, 510, 1000, or 1960 $\mu g/m^3$ (0.1, 0.26, 0.51, or 1.0 ppm) of O_3 for 72 hr and found increased lavage fluid protein content sampled immediately after exposure to concentrations $\geq$ 510 $\mu g/m^3$ (0.26 ppm) as compared with controls. Ozone-exposed guinea pigs had no accumulation of proteins when the exposure time was reduced from 72 to 3 hr, unless the time of lavage was delayed for 10 to 15 hr following exposure. The protein content of the lavage fluid determined 10 to 15 hr following a 3-hr exposure increased in a concentration-related manner from 500 to 1470 $\mu g/m^3$ (0.256 to 0.75 ppm). Again 196 $\mu g/m^3$ (0.1 ppm) had no effects. The lavage fluid protein content of guinea pigs exposed to 353 $\mu g/m^3$ (0.18 ppm) of O_3 for 8 hr per day for 5 or 10 consecutive days was not different from air controls. No effect of vitamin C deficiency could be found on the accumulation of the lavage fluid protein in guinea pigs exposed to 196 to 1470 $\mu g/m^3$ (0.10 to 0.75 ppm) O_3 for 3 hr (Hu et al., 1982). In contrast, vitamin C-deficient guinea pigs have increased sensitivity to NO_2 (Selgrade et al., 1981). Polyacrylamide gel electrophoresis of lavage fluid proteins from animals exposed for 3 hr to 196 to 1470 $\mu g/m^3$ (0.1 to 0.75 ppm) O_3 showed the appearance of extra protein bands which co-migrated with serum proteins and of increased intensity of bands that also occur in air-exposed controls. This led the authors to conclude that the main source of the increased protein was serum.

Prostaglandins are intermediates in tissue edema resulting from a wide variety of mechanisms of injury. Increased lung permeability and edema produced by O_3 might also be mediated by prostaglandins. Non-steroidal anti-inflammatory drugs (aspirin and indomethacin) at appropriate doses inhibit lung edema in rats from exposure to 7890 μg/m^3 (4 ppm) of O_3 for 4 hr (Giri et al., 1975). Prostaglandins $F_{2\alpha}$ and E_2 were markedly increased in plasma and lung lavage of rats exposed to 7840 μg/m^3 (4 ppm) for up to 8 hr (Giri et al., 1980). Ozonolysis of arachidonic acid *in vitro* produces fatty acid peroxides and other products having prostaglandin-like activity (Roycroft et al., 1977). Fatty acid cycloperoxides are produced directly by ozone-catalyzed peroxidation (Pryor, 1976; Pryor et al., 1976). Acute exposure to 5880 μg/m^3 (3 ppm) O_3 inhibits uncompetitively rat lung prostaglandin cyclooxygenase (Menzel et al., 1976).

Earlier reports that prostaglandin synthesis inhibitors exacerbated O_3-produced edema (Dixon and Mountain, 1965; Matzen, 1957), as did methyl prednisolone (Alpert et al., 1971a), tend to confuse the interpretation of the role of prostaglandin in O_3-produced injury. Prostaglandin synthesis inhibitors clearly inhibit the degradation of prostaglandins and alter the balance between alternative pathways of fatty acid peroxide metabolism. Thus, while prostanoids are highly likely to be involved in O_3-produced edema, their exact role is still unexplained.

10.3.3.9 Proposed Molecular Mechanisms of Effects. Experts generally agree that the toxicity of O_3 depends on its oxidative properties. The precise mechanism of O_3's toxicity at the subcellular level is unclear, but several theories have been advanced. These theories include the following:

1. Oxidation of polyunsaturated lipids contained mainly in cell membranes;
2. Oxidation of sulfhydryl, alcohol, aldehyde, or amine groups in low molecular weight compounds or proteins;
3. Formation of toxic compounds (ozonides and peroxides) through reaction with polyunsaturated lipids;
4. Formation of free radicals, either directly or indirectly, through lipid peroxidation; and
5. Injury mediated by some pharmacologic action, such as via a neurohormonal mechanism, or release of histamine.

These mechanisms have been discussed in several reviews: U.S. Environmental Protection Agency (1978); National Air Pollution Control Association (1970); North Atlantic Treaty Organization (1974); National Research Council

(1977); Shakman (1974); Menzel (1970, 1976); Nasr (1967); Cross et al. (1976); Pryor et al. (1983); and Mudd and Freeman (1977). From these reviews and recent research detailed here or in previous biochemistry sections, two hypotheses are favored and may in fact be related.

10.3.3.9.1 Oxidation of polyunsaturated lipids. The first hypothesis is that O_3 initiates peroxidation of polyunsaturated fatty acids (PUFA) to peroxides, which produces toxicity through changes in the properties of cell membranes. Ozone addition to ethylene groups of PUFA can take place in membranes yet give rise to water-soluble products that can find their way to the cytosol. Aldehydes, peroxides, and hydroxyl radicals formed by peroxidation all can react with proteins. In addition to the direct oxidation of amino acids by O_3, secondary reaction products from O_3-initiated PUFA peroxidation can also oxidize amino acids or react with proteins to alter the function of the proteins. Since large numbers of proteins are embedded with lipids in membranes and rely on the associated lipids to maintain the tertiary structure of the protein, alterations in the lipid surrounding the protein can result in structural changes of the membrane-embedded protein. At present, methods are not available to differentiate effects on membrane proteins from effects on membrane lipids.

Some of the strongest evidence that the toxic reaction of O_3 can be associated with the PUFA of membranes is the protective effect of dietary vitamin E on O_3 toxicity (Roehm et al., 1971a, 1972; Chow and Tappel, 1972; Fletcher and Tappel, 1973; Donovan et al., 1977; Sato et al., 1976a; Chow and Kaneko, 1979; Plopper et al., 1979; Chow et al., 1981; Chow, 1983; Mustafa et al., 1983; Mustafa, 1975). Generally, vitamin E reduced the O_3-induced increase in enzyme activities of the glutathione peroxidase system (Section 10.3.3.2) and those involved in oxygen consumption (Section 10.3.3.3). More details are provided in Table 10-5. Morphological effects due to O_3 exposure are also lessened by dietary vitamin E (Section 10.3.1.4.1.1). Although this is not the strongest evidence, vitamin E supplementation also prevented O_3-induced changes in red blood cells (Chow and Kaneko, 1979).

These data consistently show that vitamin E has a profound effect on the toxicity of O_3 in animals. They also support indirectly lipid peroxidation as a toxic lesion in animals. However, although the influence of dietary vitamin E is clear, its relation to vitamin E levels in the lung, where presumably most lipid peroxidation would occur, is poorly understood. Rats of various ages (5, 10 and 90 days old and 2 yrs old) were fed normal diets; and 90-day-old rats were fed diets containing 0, 200, and 3000 mg of vitamin E/kg diet (Stephens et al., 1983). (Most of the biochemical studies of vitamin E protective effects were conducted with diets having far less than 200 mg/kg diet.) Rats were exposed to 1764 μg/m^3 (0.9 ppm) O_3 continuously for 72 hr, and periodic morphological observations were made. Those animals on normal diets had equivalent levels of vitamin E in the lung, but responses of the different age groups differed. Animals of a given age (90 days) maintained on the three vitamin E diets had different levels of vitamin E in the lungs (5.3 to 325 μg of vitamin E/g of tissue), but morphological responses were very similar. Stephens et al. concluded that O_3-induced responses in the lung are independent of the vitamin E content of the lung. Independent interpretation of this study is not possible, since very minimal descriptions of responses were provided and the number of animals was not given. Also, others (Chow et al., 1981; Plopper et al., 1979) found that for a given age of rat, different dietary levels of vitamin E (and perhaps different lung levels as shown by Stephens et al., 1983) influenced the morphological responses of rats to O_3.

10.3.3.9.2 Oxidation of sulfhydryl or amine groups. The second hypothesis is that ozone exerts its toxicity by the oxidation of low-molecular-weight compounds containing thiol, amine, aldehyde, and alcohol functional groups and by oxidation of proteins. Mudd and Freeman (1977) present a summary of the arguments for oxidation of thiols, amines, and proteins as the primary mechanism of O_3 toxicity based upon *in vitro* exposure data. Amino acids are readily oxidized by O_3 (Mudd et al., 1969; Mudd and Freeman, 1977; Previero et al., 1964). In the following descending order of rate, O_3 oxidizes the amino acids cysteine > methionine ≥ tryptophan > tyrosine > histidine > cystine > phenylalanine. The remaining common amino acids are not oxidized by O_3. Thiols are the most readily oxidized functional groups of proteins and peptides (Mudd et al., 1969; Menzel, 1971). Tryptophan in proteins is also oxidized *in vitro* by O_3 as shown by studies of avidin, the biotin-binding protein. Oxidation of tyrosine in egg albumin by O_3 occurs *in vitro*, converting the O_3-oxidized egg albumin to a form immunologically distinct from native egg albumin (Scheel et al., 1959). Ozone inactivated human alpha-1-protease inhibitor *in vitro* (Johnson, 1980). When treated with O_3, alpha-1-protease inhibitor lost its ability to inhibit trypsin, chymotrypsin, and elastase.

Meiners et al. (1977) found that O_3 reacted in vitro with tryptophan, 5-hydroxytryptophan, 5-hydroxytryptamine, and 5-hydroxyindolacetic acid. One mole of O_3 was rapidly consumed by each mole of indole compound. Oxidation of tryptophan by O_3 also generates hydrogen peroxide. Hydrogen peroxide is a toxic substance in itself and initiates peroxidation of lipids (McCord and Fridovich, 1978). Other active O_2 species such as HO· and O_2- are formed from hydrogen peroxide (McCord and Fridovich, 1978).

The results of the oxidation of functional groups in proteins can be generally observed by reduction of enzyme activities at high concentrations of O_3 (viz., 1960 to 7840 µg/m^3, 1 to 4 ppm for several hours). Many enzymes examined (Tables 10-5 to 10-10) in tissues have decreased activities (in many cases not statistically significant) immediately following even lower level (1960 µg/m^3, 1 ppm) O_3 exposures. The enzymes decreased include those catalyzing key steps supplying reduced cofactors to other processes in the cell, such as glucose-6-phosphate dehydrogenase (DeLucia et al., 1972) and succinate dehydrogenase (Mountain, 1963). Cytochrome P-450 (Goldstein et al., 1975), the lecithin synthetase system (Kyei-Aboagye et al., 1973), lysozyme (Holzman et al., 1968), and the prostaglandin synthetase system (Menzel et al., 1976) are decreased by O_3 exposure. Respiratory control of mitochondria is lost, and mitochondrial energy production is similarly decreased (Mustafa and Cross, 1974).

Mudd and Freeman (1977) point out that proteins are the major component of nearly all cell membranes, forming 50 to 70 percent by weight. The remainder of the weight of the cell membranes is lipids (phospholipids, glycolipids, glycerides, and cholesterol). Polyunsaturated fatty acids are components of membrane phospholipids, glycolipids, and glycerides. Mudd and Freeman contend, however, that proteins are far more easily oxidized by O_3 than are lipids. Indirect evidence in support of the idea that amines in particular are oxidized preferentially by O_3 is the protective effect of p-aminobenzoic acid (Goldstein, B., et al., 1972). Rats injected with p-aminobenzoic acid were partially protected from the mortality due to high concentrations of O_3. Presumably, the added p-aminobenzoic acid is oxidized by O_3 in place of proteins. Goldstein and Balchum (1974) later suggested that the protection of p-aminobenzoic acid, allylisopropylacetamide, and chlorpromazine was due to the induction of mixed function oxidase systems rather than a direct free radical scavenging effect. However, they also recognized that chlorpromazine can mask free radicals and result in membrane stabilization, which could account for the protective effects of these compounds preventing edema and inflammation. Acetylcholinesterase found on red blood cells is protected from inhibition by *in vitro* exposure to 78,400 µg/m^3 (40 ppm) O_3 through p-aminobenzoic acid treatment (Goldstein, B., et al., 1972). Amines are also efficient lipid antioxidants, so the results of these experiments could be interpreted in favor of the theory of peroxidation of the cell membrane as a mechanism of toxicity, as well.

10.3.3.9.3 Formation of toxic compounds through reaction with polyunsaturated lipids. The effects of O_3 could be due to the elaboration of products of peroxidation as well as peroxidation of the membrane itself. Menzel et al. (1973) injected 10 pg to 10 µg of fatty acid ozonides from oleic, linoleic, linolenic, and arachidonic acids into animals and found increased vascular permeability measured by extravascularly located Pontamine Blue dye bound to serum proteins. Extravascularization of serum proteins could be blocked by simultaneous antihistamine injection or by prior treatment with compound 48/80, a substance that depletes histamine stores. Cortesi and Privett (1972) injected methyl linoleate ozonide into rats or gave the compound orally; in each case acute pulmonary edema resulted. The pulmonary edema and changes in fatty acid composition of the serum and lung lipids were similar to those occurring after O_3 exposure (Roehm et al., 1971a,b, 1972; Menzel et al., 1976).

Peroxidation of lung lipids could lead to cytotoxic products. Phosphatidyl choline liposomes (spheres formed by emulsifying phosphatidyl choline in water) were lysed on exposure to O_3 (Teige et al., 1974). Liposomes exposed to O_3 were more active than O_3 alone in lysing red blood cells. The products of ozonolysis of phosphatidyl choline could be stable, yet toxic, intermediates.

10.3.3.9.4 Formation of free radicals and injury mediated by pharmacologic action. The other theories may be linked to the consequences of peroxidation of PUFA. Ozonation of PUFA results in the formation of peroxides (e.g., ROOH or ROOR) rather than oxidation of alkenes to higher oxidation states (e.g., ROH, RCHO or RCO2H). Peroxides (ROOH or ROOR) are chemically reactive and may be the ultimate toxicants, not simply products of oxidation. During the process of peroxidation or direct addition of O_3 to PUFA, free radicals may be generated (Pryor et al., 1983), and these free radicals may be the ultimate toxicants.

Because the metabolism of PUFA peroxides in the lungs is intimately linked with the metabolism of thiol compounds (such as glutathione, GSH), direct oxidation of thiols by O_3 (hypothesis B) may link the two major hypotheses A and B with hypothesis C, formation of toxic products. Ozone depletion of GSH could render the peroxide detoxification mechanism ineffective. However, at levels of O_3 below 1960 $\mu g/m^3$ (1 ppm), increases in glutathione have been observed (Plopper et al., 1979; Fukase et al., 1975; Moore et al., 1980; Mustafa et al., 1982). The rat lung is sensitive to the increase of glutathione peroxidase, glutathione reductase, and glucose-6-phosphate dehydrogenase activities at levels as low as 196 $\mu g/m^3$ (0.1 ppm) O_3 continuously for 7 days (Plopper et al., 1979; Chow et al., 1981; Mustafa, 1975; Mustafa and Lee, 1976) in vitamin E deficient rats. With vitamin E-supplemented rats, 392 $\mu g/m^3$ (0.2 ppm) caused similar effects. After acute exposures to >1960 $\mu g/m^3$ (1 ppm) O_3, decreases are observed in these enzyme activities and glutathione levels. Other species (mice and monkeys) exhibit similar effects at different concentrations (Table 10-5). These changes at the lower levels of O_3 appear to be coincidental with the initiation of repair and proliferative phases of lung injury (Cross et al., 1976; Dungworth et al., 1975a,b; Mustafa and Lee, 1976; Mustafa et al., 1977, 1980; Mustafa and Tierney, 1978). The parallel increase in the number of type 2 cells having higher levels of metabolic activity would be expected to cause an overall increase in the metabolic activity of the lung. This was substantiated by Mustafa (1975) and DeLucia et al. (1975a), who found that the O_2 consumption per mitochondrion was not increased in O_3-exposed lungs but that the number of mitochondria was increased. Chow and Tappel (1972) proposed that alterations of enzymatic activity were due to stimulation of glutathione peroxidase pathway. Chow and Tappel (1973) also proposed that the changes in the pentose shunt and glycolytic enzymes in lungs of the O_3-exposed rats were due to the demands of the glutathione peroxidase system for reducing equivalents in the form of NADPH. Cross et al. (1976) and DeLucia (1975a,b) reported that O_3 exposure oxidized glutathione and formed mixed disulfides between proteins and non-protein sulfhydryl compounds.

The general importance of glutathione in preventing lipid peroxidation in the absence of O_3 has been shown by Younes and Siegers (1980) in rat and mouse liver where depletion of glutathione by treatment with vinylidene chloride or diethylmaleate led to increased spontaneous peroxidation. These authors suggest that glutathione prevents spontaneous peroxidation by suppression of radicals formed by the enzyme cytochrome P-450 or already produced hydroperoxides.

Chow and Tappel (1973) suggest that peroxides formed via lipid peroxidation increase glutathione peroxidase activity and, in turn, increase levels of the enzymes necessary to supply reducing equivalents (NADPH) to glutathione reductase. Vitamin E suppresses spontaneous formation of lipid peroxides and, therefore decreased the glutathione peroxidase activity in mouse red cells (Donovan and Menzel, 1975; Menzel et al., 1978). The supplementation of rats with vitamin E could, therefore, decrease the utilization of glutathione by spontaneous reaction or by ozone-initiated peroxidation. The two mechanisms could then interact in a concerted fashion to decrease ozone cytotoxicity. Eliminating vitamin E from the diet increases the chances of increases of this system.

In support of hypothesis E, Wong and Hochstein (1981) found that thyroxin enhanced the osmotic fragility of human erythrocytes exposed to O_3 _in vitro_. They found also that ^{125}I from radiolabeled thyroxin was incorporated into the major membrane glycoprotein, glycophorin, of red cells. When these events had occurred, the cation permeability of the human red cells was enhanced without measurable inhibition of ATPase or membrane lipid peroxidation. They suggested that thyroid hormones play an important role in O_3 toxicity. Fairchild and Graham (1963) found that thyroidectomy, thiourea, and antithyroid drugs protected animals from lethal exposures to O_3 and nitrogen dioxide. Fairchild and Graham ascribed the mortality following O_3 to pulmonary edema. Wong and Hochstein (1981) suggested that O_3 toxicity in the lung may be altered through a free radical mechanism involving iodine transfer from thyroxin to lung membranes. The hormonal status of animals could alter a variety of defense mechanisms and O_3 sensitivity.

10.3.3.9.5 Summary. The actual toxic mechanism of O_3 may involve a mixture of all of these chemical mechanisms because of the interrelationships between the peroxide detoxification mechanisms and glutathione (See Section 10.3.3.2) and the complexity of the products produced from ozonation of PUFA. A single chemical reaction may not be adequate to explain O_3 toxicity. The relative importance of any one reaction, oxidation of proteins, PUFA, or small molecular weight compounds, will depend upon a number of factors such as the presence of enzymatic pathways of decomposition of products formed (peroxides), pathways for regeneration of thiols, the presence of non-enzymatic means of terminating free radical reactions (vitamins E and C), and differences in membrane composition of PUFA (relative ease of attack of O_3), for example.

10.3.4 Effects on Host Defense Mechanisms

The mammalian respiratory tract has a number of closely coordinated pulmonary defense mechanisms that, when functioning normally, provide protection from the adverse effects of a wide variety of inhaled microbes and other particles. A variety of sensitive and reliable methods have been used to assess the effects of O_3 on the various components of this defense system to provide a better understanding of the health effects of this pollutant.

The previous *Air Quality Criteria Document for Ozone and Photochemical Oxidants* (U.S. Environmental Protection Agency, 1978) provided a review and evaluation of the scientific literature published up to 1978 regarding the effects of O_3 on host defenses. Other reviews have recently been written that provide valuable references to the complexity of the host defense system and the effects of environmental chemicals such as O_3 on its integrity (Gardner, 1981; Ehrlich, 1980; Gardner and Ehrlich, 1983).

This section describes the existing data base and, where appropriate, provides an interpretation of the data, including an assessment of the different microbial defense parameters used, their sensitivity in detecting abnormalities, and the importance of the abnormalities with regard to the pathogenesis of infectious disease in the exposed host. This section also discusses the various components of host defenses, such as the mucociliary escalator and the alveolar macrophages, which clear the lung of both viable and nonviable particles, and integrated mechanisms, which are studied by investigating the host's response to experimentally induced pulmonary infections. The immune system, which defends the overall host against both infectious and neoplastic diseases, is also discussed.

10.3.4.1 Mucociliary Clearance. The mucociliary system is one of the lung's primary defense mechanisms. It protects the conducting airways by trapping and quickly removing material that has been deposited or is being cleared from the alveolar region. The effectiveness of mucociliary clearance can be determined by measuring such biological activities as the rate of transport of deposited particles; the frequency of ciliary beating; structural integrity of the ciliated cells; and the size, number, and distribution of mucus-secreting cells. Once this defense mechanism has been altered, a buildup of both viable and nonviable inhaled substances can occur on the epithelium and may jeopardize the health of the hose, depending on the nature of the uncleared substance.

A number of studies with various animal species have reported morphological damage to the cells of the tracheobronchial tree from acute and subchronic exposure to 490 to 1960 $\mu g/m^3$ (0.20 to 1.0 ppm) of O_3. (See Section 10.3.1.) The cilia were either completely absent or had become noticeably shorter or blunt. By removing these animals to a clean-air environment, the structurally damaged cilia regenerated and appeared normal. Based on such morphological observations, related effects such as ciliostasis, increased mucus secretions, and a slowing of mucociliary transport rates might be expected. However, no measurable changes in ciliary beating activity have been reported due to O_3 exposure alone. Assay of isolated tracheal rings from hamsters immediately after a 3-hr exposure to 196 $\mu g/m^3$ (0.1 ppm) of O_3 showed no significant loss in ciliary beating activity (Grose et al., 1980). In the same study, when the animals were subsequently exposed for 2 hr to 1090 μg of H_2SO_4 per cubic meter (0.30 μm volume median diameter), a significant reduction in ciliary beating frequency occurred. The magnitude of this effect was, however, significantly less than that observed due to the effect of H_2SO_4 exposure alone. In either case, the animals completely recovered within 72 hr when allowed to remain in a clean-air environment. These authors found only a slight decrease in beating frequency with a simultaneous exposure to 196 $\mu g/m^3$ (0.1 ppm) of O_3 and 847 $\mu g/m^3$ H_2SO_4 (Grose et al., 1982). These data indicate that O_3 appears to partially protect against the effects of H_2SO_4 on ciliary beating frequency. Grose et al. (1982) proposed that the ciliary cells may be partially protected due to the increase in mucus tracheal secretion of glycoproteins (Last and Cross, 1978) resulting from exposure to these chemicals.

Studies cited in the previous criteria document (U.S. Environmental Protection Agency, 1978) gave evidence on the effect of O_3 on the host's ability to physically remove deposited particles (Table 10-11). The slowing of mucus transport in both rat and rabbit trachea as a result of O_3 exposure was reported in the early literature (Tremer et al., 1959; Kensler and Battista, 1966). Goldstein, E., et al. (1971a,b, 1974) provided evidence that the primary effect of O_3 on the defense mechanism of the mouse lung was to diminish bactericidal activity but not to significantly affect physical removal of the deposited bacteria. In these studies, mice were exposed to an aerosol of 32P-labeled Staphylococcus aureus either after a 17-hr exposure to O_3 or

TABLE 10-11. EFFECTS OF OZONE ON HOST DEFENSE MECHANSIMS: DEPOSITION AND CLEARANCE

Ozone concentration		Measurement[a] method	Exposure duration and protocol	Observed effects	Species	Reference
μg/m³	ppm					
196	0.1	CHEM	3 hr	No effect on ciliary beating frequency.	Hamster	Grose et al., 1980
784	0.4	NBKI	3 hr	Initially lowers deposition of inhaled bacteria, but subsequently a higher number are present due to reproduction.	Mouse	Coffin and Gardner, 1972b
784	0.4	ND	4 hr	Bactericidal activity inhibited. Silicosis did not enhance O_3 effect.	Mouse	Goldstein, E., et al., 1972
785, 1568, 1960	0.4, 0.8, 1.0	UV	4 hr	Delay in mucociliary clearance, acceleration in alveolar clearance.	Rat	Kenoyer et al., 1981
1764	0.5	MAST	1.4 hr	Increases nasal deposition and growth of virus; no effect in the lungs.	Mouse	Fairchild, 1974, 1977
980	0.5	NBKI	16 hr/day, 7 months	No effect on clearance of polystyrene and iron particles.	Rabbit	Friberg et al., 1972
980	0.5	NBKI	2 months	Reduced clearance of viable bacteria.	Guinea pig	Friberg et al., 1972
980, 1960	0.5, 1.0	CHEM	2 hr	Reduced tracheal mucus velocity at 1.0 ppm. No effect at 0.5 ppm.	Sheep	Abraham et al., 1980
784	0.57-2.03	M	17 hr before bacteria	Physical clearance not affected, but bactericidal activity affected at 0.99 ppm. Decrease in deposition of inhaled organisms at 0.57 ppm.	Mouse	Goldstein et al., 1971a

TABLE 10-11. EFFECTS OF OZONE ON HOST DEFENSE MECHANISMS: DEPOSITION AND CLEARANCE (continued)

Ozone concentration μg/m³	Ozone concentration ppm	Measurement[a] method	Exposure duration and protocol	Observed Effects	Species	Reference
1176	0.62-4.25	M	4 hr after bacteria	No effect on bacterial deposition and clearance; reduced bactericidal activity at each exposure level.	Mouse	Goldstein et al., 1971b
1372	0.7	M	7 days	Deficiency of Vitamin E further reduced bactericidal activity after 7 days.	Rat	Warshauer et al., 1974
1372	0.7	G	3-4 hr	Reduced bactericidal activity in lungs.	Mouse	Bergers et al., 1982
1568	0.8	UV	4 hr	Slowed tracheobronchial clearance and accelerated alveolar clearance. Effects greater with higher humidity.	Rat	Phalen et al., 1980
1960	1.0	NBKI	3 hr	Bacteria clear lung and invade blood.	Mouse	Coffin and Gardner, 1972b
2352	1.2	UV	4 hr	Delayed mucociliary clearance of particles.	Rat	Frager et al., 1979

[a] Measurement method: ND = not described; CHEM = gas phase chemiluminescence; UV = UV photometry; NBKI = neutral buffered potassium iodide; MAST = KI-coulometric (Mast meter); M = microcoulomb sensor; G = galvanic meter.

before a 4-hr exposure. Concentrations of O_3 were 1180, 1370, 1570, or 1960 $\mu g/m^3$ (0.6, 0.7, 0.8, or 1.0 ppm). The mechanical clearance and bactericidal capabilities of the lung were then measured 4 to 5 hr after bacterial exposure. Exposure 17 hr before infection caused a significant reduction in bactericidal activity beginning at 1960 $\mu g/m^3$ (1.0 ppm) of O_3. When mice were exposed to O_3 for 4 hr after being infected, there was a significant decrease in bactericidal activity for each O_3 concentration, and with increasing O_3 concentration, there was a progressive decrease in bactericidal activity. The investigators proposed that because mucociliary clearance was unaffected by subsequent O_3 exposure, the bactericidal effect was due to dysfunction of the alveolar macrophage.

Friberg et al. (1972) studied the effect of a 16-hr/day exposure to 980 $\mu g/m^3$ (0.5 ppm) of O_3 on the lung clearance rate of radiolabeled monodispersed polystyrene and iron particles in the rabbit and of bacteria in the guinea pig. The results from the guinea pig studies showed a reduced clearance of viable bacteria. The rabbit's lung clearance rate was not affected by O_3. In this latter study, however, a large number of the test animals died during exposure from a respiratory disease, and the results must be viewed with caution.

Recent studies have continued to examine the effects of O_3 on mucociliary transport in the intact animal. Phalen et al. (1980) attempted to quantitate the removal rates of deposited material in the upper and lower respiratory tract of the rat. In this study, the clearance rates of radiolabeled monodisperse polystyrene latex spheres were followed after O_3 exposure. A 4-hr exposure to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 significantly slowed the early (tracheobronchial) clearance and accelerated the late (alveolar) clearance rates at both low (30 to 40 percent) and high (> 80 percent) relative humidity. These effects were even greater at higher humidity, which produced nearly additive effects. Combining O_3 with various sulfates [$Fe_2(SO_4)_2$, H_2SO_4, $(NH_4)_2SO_4$] gave clearance rates very similar to those for O_3 alone. Accelerating the long-term clearance from the alveoli may not in itself be harmful; however, because this process may result from an influx of macrophages into the alveolar region, the accumulation of excess numbers of macrophages might present a potential health hazard because of their high content of proteolytic enzymes and O_2 free radicals, which have the capability for tissue destruction. Essentially no data are available on the effects of prolonged exposure to O_3

on ciliary functional activity or on mucociliary transport rates measured in the intact animal.

Frager et al. (1979) deposited insoluble, radioactive-labeled particles via inhalation and monitored the clearance rate after a 4-hr exposure to 2352 µg/m^3 (1.2 ppm) of O_3. This exposure caused a substantial delay in rapid (mucociliary) clearance in the rat. However, if the animals were exposed 3 days earlier to 1568 µg/m^3 (0.8 ppm) of O_3 for 4 hr, the pre-exposure eliminated this effect, resulting in a clearance rate that was essentially the same as for controls. Thus, the pre-exposure to a lower level 3 days before rechallenging with a higher concentration of O_3 appeared to afford complete protection at 3 days. After a 13-day interval between the pre-exposure and the challenges, this adaptation or tolerance was lost.

These results were confirmed when Kenoyer et al. (1981) repeated these studies, with three different concentrations of O_3, 784, 1568, and 1960 µg/m^3 (0.4, 0.8, and 1.0 ppm). At each of the three concentrations, a delay was observed in early (0 to 50 hr postdeposition of particles) clearance, and an acceleration was seen in long-term (50 to 300 hr postdeposition) clearance, as compared to controls. Concentration-response curves showed that clearance was affected more by the higher concentrations of O_3.

The velocity of the tracheal mucus of sheep was not significantly altered from a baseline value of 14.1 mm/min after a 2-hr exposure to 980 µg/m^3 (0.5 ppm) of O_3 (Abraham et al., 1980). The authors state that 1960 µg/m^3 (1 ppm) of O_3 for 2 hr did significantly reduce, both immediately and 2 hr postexposure, the tracheal mucus velocity.

10.3.4.2 Alveolar Macrophages. Within the gaseous exchange region of the lung, the first line of defense against microorganisms and nonviable insoluble particles is the resident population of alveolar macrophages. These cells are responsible for a variety of important activities, including detoxification and removal of inhaled particles, maintenance of pulmonary sterility, and interaction with lymphoid cells for immunological protection. In addition, macrophages act as scavengers by removing cellular debris. To adequately fulfill their purpose, these defense cells must maintain active mobility, a high degree of phagocytic activity, an integrated membrane structure, and a well-developed and functioning enzyme system. Table 10-12 illustrates the effect of O_3 on the alveolar macrophage (AM).

TABLE 10-12. EFFECTS OF OZONE ON HOST DEFENSE MECHANISMS: MACROPHAGE ALTERATIONS

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effects[c]	Species	Reference
μg/m³	ppm					
196 1960	0.1 1.0	NBKI	2.5 hr or 30 min *in vitro*	Lung protective factor partially inactivated, increasing fragility of macrophages (concentration-related).	Rabbit	Gardner et al., 1971
392	0.2	MAST NBKI	8 hr/day for 7 days	Increased number of macrophages in lungs (morphology).	Monkey Rat	Castleman et al., 1977 Dungworth, 1976 Stephens et al., 1976
490 980	0.25 0.50	NBKI	3 hr (*in vivo* and *in vitro*)	Decreased activity of the lysosomal enzymes lysozyme, acid phosphatase, and β-glucuronidase.	Rabbit	Hurst et al., 1970, 1971
980	0.5	NBKI	8 hr/day for 7 days	Increased osmotic fragility.	Rabbit	Dowell et al., 1970
980	0.5	NBKI	3 hr	Decreased enzyme activity and increased influx of PMNs.	Rabbit	Alpert et al., 1971b
980	0.5	CHEM	3 hr	Decreased red blood cell rosette binding to macrophages.	Rabbit	Hadley et al., 1977
980 1313	0.5 0.67	NBKI	3 hr	Decreased ability to ingest bacteria.	Rabbit	Coffin et al., 1968b Coffin and Gardner, 1972b
980 1960	0.5 1	NBKI	2 hr (*in vitro*)	Decreased agglutination in the presence of concanavalin A.	Rat	Goldstein et al., 1977
1058	0.54	UV	23 hr/day for 34 days	Increased number of macrophages (morphological).	Mouse	Zitnik et al., 1978

TABLE 10-12. EFFECTS OF OZONE ON HOST DEFENSE MECHANISMS: MACROPHAGE ALTERATIONS (continued)

Ozone concentration $\mu g/m^3$	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effects[c]	Species	Reference
1568	0.8	ND	11 and 24 days	No effect on *in vitro* interferon production.	Mouse	Ibrahim et al., 1976
1568	0.8	ND	90 days	Eightfold increase in number of macrophages at 7 days, reducing to fourfold after 90 days.	Rat	Boorman et al., 1977
1568	0.8	UV	7 days	Decreased number of migrating macrophages and total distance migrated.	Monkey	Schwartz and Christman, 1979
1568	0.8	MAST	3, 7, 20 days	Increased phagocytosis.	Rat	Christman and Schwartz, 1982
1960 9800	1 5	CHEM	3 hr	Decreased ability to produce interferon *in vitro*.	Rabbit	Shingu et al., 1980
1960	1	UV	4 hr	Decreased *in vitro* migrational ability, as evidenced *by* decreased number of macrophages able to migrate.	Rat	McAllen et al., 1981
3136 6860	1.6 to 3.5	NBKI	2 hr to 3 hr	Decreased superoxide anion radical production.	Rat	Amoruso et al., 1981 Witz et al., 1982
4900	2.5	M	5 hr	Loss of β-glucuronidase and acid phosphatase in PAM with ingested bacteria; decreased rate of bacterial ingestion.	Rat	Goldstein et al., 1978b
4900	2.5	M	5 hr	Diminished rate of bacterial killing, increased numbers of intracellular staphylococcal clumps; lack of lysozyme in macrophages with staphylococcal clumps.	Rat	Kimura and Goldstein, 1981

[a] Measurement method: ND = not described; CHEM = gas phase chemiluminescence; UV = UV photometry; NBKI = neutral buffered potassium iodide; MAST = KI-coulometric (Mast meter); M = microcoulomb sensor.

[b] Calibration method: NBKI = neutral buffered potassium iodide.

[c] Abbreviations used: PMN = polymorphonuclear leukocytes; PAM = pulmonary alveolar macrophage.

Under normal conditions, the number of free AMs located in the alveoli is relatively constant when measured by lavage (Brain et al., 1977, 1978). Initially, O_3, through its cytolytic action that is probably mediated through its action on the cell membrane, significantly reduces the total number of these defense cells immediately after exposure (Coffin and Gardner, 1972b). The host responds with an immediate influx of reserve cells to aid the lung in combating this assault. Little is known about the mechanisms of action that stimulate this migration or about the fate of these immigrant cells. The source of these new cells may be either (1) the influx of interstitial macrophages, (2) the proliferation of interstitial macrophagic precursors with subsequent migration of the progeny into the air space, (3) migration of blood monocytes, or (4) division of free AMs. The rapid increase in the number of macrophages is evidently a biphasic response, arising from an early phase apparently correlated to a local cellular response and a later phase of interstitial cell proliferation, which is responsible for the maintenance of the high influx of macrophages (Brain et al., 1978).

Morphological studies have supported the observation that exposure to O_3 can result in a macrophage response in several animal species. Exposure of mice to 1058 $\mu g/m^3$ (0.54 ppm) of O_3 23 hr/day for a maximum of 34 days resulted in an increased number of macrophages within the proximal alveoli of the alveolar ducts (Zitnik et al., 1978). These cells were highly vacuolated and contained many secondary phagocytic vacuoles filled with cellular debris. The effect was most prominent after 7 days of exposure and became less evident as the exposure continued. This observation correlated with the finding in rats of an eightfold increase in the number of pulmonary free cells after exposure to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 for 7 days, but only a fourfold increase after exposure for 90 days (Brummer et al., 1977; Boorman et al., 1977). In similar studies, other authors found that both monkeys and rats exposed to concentrations as low as 392 $\mu g/m^3$ (0.2 ppm) of O_3 for 8 hr/day on 7 consecutive days resulted in an accumulation of macrophages in the lungs of these exposed animals (Castleman et al., 1977; Dungworth, 1976; Stephens et al., 1976). The data from these studies suggest that these two species of animals are approximately equal in susceptibility to the short-term effects of O_3.

Thus, the total available data would indicate that, after short periods of O_3 insult, there is a significant reduction in the number of free macrophages available for pulmonary defense, and that these macrophages are more fragile, are less phagocytic, and have decreased enzymatic activity (Dowell et al., 1970; Coffin et al., 1968b; Coffin and Gardner, 1972b; Hurst et al., 1970). However, histological studies have reported that with longer exposure periods, there is an influx and accumulation of macrophages within the airways. Such a marked accumulation of macrophages within alveoli may appear to be a reasonable response to the immediate insult, but it has been speculated that the consequences of this mass recruitment may also be instrumental in the development of future pulmonary disease due to the release of proteolytic enzymes by the AMs (Brain, 1980; Menzel et al., 1983).

A decrease in the ability of macrophages to phagocytize bacteria after exposure to concentrations as low as 980 µg/m^3 (0.5 ppm) of O_3 for 3 hr was demonstrated by Coffin et al. (1968b). However, Christman and Schwartz (1982) may have demonstrated that with longer exposure periods, the effects may be different (i.e., the phagocytic rate may increase). In this study, rats were exposed to 1568 µg/m^3 (0.8 ppm) of O_3 for 3, 7 or 20 days; at those times the macrophages were isolated, allowed to adhere to glass, and incubated with carbon-coated latex microspheres. The percentages of phagocytic cells were determined at 0.25, 0.5, 1, 2, 4, 8 and 24 hr of incubation. At all exposure time periods tested, the number of spheres engulfed had increased. The greatest increase in phagocytic activity was observed after 3 days of exposure. The exposed cells engulfed a greater number of spheres than controls, and a larger percentage of macrophages from exposed animals was phagocytic. This enhancement correlated well with a significant increase in cell spreading of AMs from exposed rats as compared to controls. If O_3 enhances macrophage function and causes a migration of macrophages into the lung, the comparisons of function of these new cells with controls may not be valid, because these new cells are biochemically younger. Another significant problem with this study is that the cells examined were a selected population because only the cells that adhered to the glass surface were available for study. The cells that did not adhere were removed by washing. In this study, only 51 percent of the collected cells adhered after 3 days of O_3 exposure, compared to 85 percent of the controls. Although the effects of O_3 on cell attachment have not been studied directly, there is evidence that O_3 affects AM membranes involved in the attachment process (Hadley et al., 1977; Dowell et al., 1970; Aranyi et al., 1976; Goldstein et al., 1977). The cells most affected by the cytotoxic action of the O_3 exposure might never have been tested, because they were discarded.

Goldstein et al. (1977) studied the effect of a 2-hr exposure on the ability of AM to be agglutinated by concanavalin-A, a parameter reflecting membrane organization. A decrease in agglutination of rat AMs was found after exposure to 980 or 1960 $\mu g/m^3$ (0.5 or 1.0 ppm) of O_3. A decrease in concanavalin-A agglutinability of trypsinized red blood cells obtained from rats exposed for 2 hr to 1960 $\mu g/m^3$ (1 ppm) was also noted. Hadley et al. (1977) investigated AM membrane receptors from rabbits exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3 for 3 hr. Following O_3 exposure, lectin-treated AMs have increased rosette formation with rabbit red blood cells. The authors hypothesized that the O_3-induced response indicates alterations of macrophage membrane receptors for the wheat germ agglutinin that may lead to changes in the recognitive ability of the cell.

Ehrlich et al. (1979) studied the effects of O_3 and NO_2 mixtures on the activity of AMs isolated from the lungs of mice exposed for 1, 2, and 3 months. Only after a 3-month exposure to the mixture of 196 $\mu g/m^3$ (0.1 ppm) of O_3 and 0.5 ppm of NO_2 (3 hr/day, 5 days/week) did viability in macrophages decrease significantly. In vitro phagocytic activity was also not affected by a 1-month exposure to this level of pollutants, but after 2- and 3-month exposures the percentage of macrophages that had phagocytic activity decreased significantly.

A number of integrated steps are involved in phagocytosis processes, the first being the ability of the macrophage to migrate to the foreign substance on stimulus. McAllen et al. (1981) studied the effects of 1960 $\mu g/m^3$ (1.0 ppm) of O_3 for 4 hr on the migration rate of AMs. Migration was measured by determining the area macrophages could clear of gold-colloid particles that had been previously precipitated onto cover slips. In this study, it was not clear whether the gold was actually ingested or merely adhered to the outer surface of the cell. Nevertheless, the cells from O_3-exposed rats appeared less mobile, in that they migrated 50 percent less than the sham-exposed group.

It has been reported that the acellular fluid that lines the lungs also plays an important role in defense of the lung through its interaction with pulmonary macrophages (Gardner et al., 1971; Gardner and Graham, 1977). These studies demonstrated that the protective components of this acellular fluid can be inactivated by a 2.5-hr exposure to 196 $\mu g/m^3$ (0.1 ppm) of O_3. When normal AM's are placed in fluid lavaged from O_3-exposed animals, they showed an increase in lysis (10 percent over control). A similar effect was seen when normal AM's were placed in protective fluid that had been exposed *in vitro* to O_3. The data indicate that some of the effects of O_3 on lung cells may be mediated through this lung lining fluid. Schwartz and Christman (1979) provided evidence that normal lung lining material enhanced macrophage migration, but the macrophages obtained from rhesus monkeys after exposure for 7 days to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 demonstrated both a decrease in the number of cells that migrated (28 percent of control value) and in the total distance they traveled (71 percent of control value). Adding normal lining fluid to isolated O_3-exposed macrophages did enhance the migration, but it was still significantly less than controls.

Macrophages are rich in lysosomal enzymes. Because these enzymes are crucial in the functioning of the macrophage, any perturbation of the metabolic or enzymatic mechanisms of these cells may have important consequences on the abilities of the lung to defend itself against disease. Enzymes that have been identified include acid phosphatase, acid ribonuclease, beta galactosidase, beta glucuronidase, cytochrome oxidase, lipase, lysozyme, and protease. Ozone decreased significantly the activity levels of lysozyme, β-glucuronidase, and acid phosphatase in rabbit macrophages after a 3-hr exposure of rabbits to concentrations as low as 490 $\mu g/m^3$ (0.25 ppm) of O_3 (Hurst et al., 1970). Such enzymatic reductions were also observed in AMs exposed *in vitro* (Hurst et al., 1971). The ability of O_3 to alter macrophages' enzyme activity was also studied by means of unilateral lung exposure of rabbits (Alpert et al., 1971b). A significant reduction in these same three intracellular enzymes was found to be specific to the lung that breathed O_3 rather than a generalized systemic response. These effects were concentration-related, beginning at 980 $\mu g/m^3$ (0.5 ppm) of O_3. The extracellular release of such enzymes may occur either as a result of direct cytotoxic damage and leakage of intracellular contents, or they may be selectively released without any cell injury. Hurst et al. (1971) showed that the reduction in intracellular lysosomal enzyme activity observed after *in vitro* exposure coincides with the release of the enzyme into the surrounding medium. In these studies, the sum of the intra- plus extracellular enzyme activity did not equal the total activity, indicating that the pollutant itself can inactivate the hydrolytic enzyme as well as alter the cell membrane. Recently, Witz et al. (1982) and Amoruso et al. (1981) reported that *in vivo* O_3 exposure affected the production of superoxide anion radicals (O_2) by rat AMs. This oxygen radical is important in antibacterial activity.

Exposure to concentrations above 3136 μg/m^3 (1.6 ppm) of O_3 for 2 hr appears to result in a progressive decrease in O_2^- production. No statistical evaluation of the data was performed. The type of membrane damage as well as the mechanisms by which this damage is incurred are not well understood. It is not known whether the O_3-induced inhibition of O_2^- production arises from the direct oxidative damage of the membrane enzyme involved in the metabolism of O_2 to O_2^-, or whether it is a result of oxidative degradation of membrane lipids that may serve as a cofactor function.

Shingu et al. (1980) reported the effects of O_3 on the ability of two cell types, macrophages and tonsillar lymphocytes, to produce interferon, a substance that aids in defending the host organism against viral infections. Macrophages from rabbits exposed to 1960 μg/m^3 (1.0 ppm) of O_3 for 3 hr exhibited a depression in interferon production. Interferon production by tonsillar lymphocytes was not significantly depressed by 9800 μg/m^3 (5.0 ppm) of O_3. The authors suggested that an impairment of interferon production might play an important role in the ability of the host to combat respiratory viral infections. In neither of the studies were statistical analyses of the data reported. Ibrahim et al. (1976) also exposed mice to O_3 and illustrated that 1568 μg/m^3 (0.8 ppm) of O_3 for a period of 11 days inhibited the in vitro ability of tracheal epithelial cells to produce interferon.

10.3.4.3 Interaction with Infectious Agents. In general, the consequences of any toxic response depend on the particular cell or organ affected, the severity of the damage, and the capability of the impaired cells or tissue to recover from the assault. Do small decrements in the functioning of these various host defense mechanisms compromise the host so that it is unable to defend itself against a wide variety of opportunistic pathogens? Measurement of the competency of the host's antimicrobial mechanisms can best be tested by challenging both the toxic-exposed animals and the clean-air exposed control animals to an aerosol of viable microorganisms. If the test substance, such as O_3, had any adverse influence on the efficiency of any of the host's many protective mechanisms (i.e., mechanical clearance via the mucociliary escalator, biological clearance mediated through macrophages, and associated cellular and humoral immunological events) that would normally function in defending the host against this microbe, the microbe, in its attempt to survive, would take advantage of these weaknesses. A detailed description of the infectivity model commonly used for O_3 studies has been published elsewhere (Coffin and Gardner, 1972b; Ehrlich et al., 1979; Gardner, 1982a). Briefly, animals are randomly selected to be exposed to either clean air or O_3. After the exposure ends, the animals from both chambers are combined and exposed to an aerosol of viable microorganisms. The vast majority of these studies have been conducted with Streptococcus sp. At the termination of this 15- to 20-min exposure, the animals are housed in clean air, and the rate of mortality in the two groups is determined during a 15-day holding period. In this system, the concentrations of O_3 used do not cause any mortality. The mortality in the control group (clean air plus exposure to the microorganism) is approximately 10 to 20 percent and reflects the natural resistance of the host to the infectious agent. The difference in mortality between the O_3-exposure group and the controls is concentration-related (Gardner, 1982a).

If the test agent does not prevent the host's defense mechanisms from functioning normally, there is a rapid inactivation of inhaled microorganisms that have been deposited in the respiratory system. However, if the gaseous exposure alters the ability of these defense cells to function, the number of microbes in the lungs increases rapidly (Coffin and Gardner, 1972b; Miller et al., 1978; Gardner, 1982a). This acceleration in bacterial growth is attributed to the pollutant's alteration of the capability of the lung to destroy the inhaled bacteria, thus permitting those with pathogenic potential to multiply and produce respiratory pneumonia. With this accelerating growth, there is an invasion of the blood, and death could be predicted from a positive blood culture (Coffin and Gardner, 1972b).

Coffin et al. (1968a) treated mice with O_3 (0.08 ppm for 3 hr) and subsequently exposed them to an aerosol of infectious Streptococcus sp. In this study, O_3 increased the animals' susceptibility to infection, resulting in a significant increase in mortality rate in the O_3-treated group. Ehrlich et al. (1977), when using the same bacteria but a different strain of mice, found a similar effect at 0.1 ppm for 3 hr. When using CD-1 mice and Streptococcus sp., Miller et al. (1978) studied the effects of a 3-hr exposure to O_3 at 196 $\mu g/m^3$ (0.1 ppm) in which the bacterial aerosol was administered either immediately or 2, 4, or 6 hr after cessation of the O_3 exposure. In each replicate experiment, 20 mice per group were used, and O_3 was monitored continuously by chemiluminescence. For these postexposure challenges, only the 2-hr time resulted in a significant increase in mortality (6.7 percent) over controls.

However, when the animals were infected with Streptococci during the actual O_3 exposure, a significant increase in mortality of 21 percent was observed. When this latter experimental regimen was used, exposure to 157 μg/m^3 (0.08 ppm) of O_3 resulted in a significant increase in mortality of 5.4 percent.

The differences in results among these studies may have been due to a variation in the sensitivity of the method of O_3 monitoring, a difference in mouse strain, changes in the pathogenicity of the bacteria, or differences in sample size. The results from such studies that use this infectivity model indicate the model's sensitivity for detecting biological effects at low pollutant concentrations and its response to modifications in technique (i.e., using different mouse strains or varying the time of bacterial challenge). The model is supported by experimental evidence showing that pollutants (albeit at different concentrations) that cause an enhancement of mortality in the infectivity system also cause reductions in essential host defense systems, such as pulmonary bactericidal capability, the functioning of the alveolar macrophage, and the cytological and biochemical integrity of the alveolar macrophage.

The pulmonary defenses in the O_3-treatment group were significantly less effective in combating the infectious agent to the extent that, even at this low concentration, there was a significant increase in mortality rate in this group over controls. As the O_3 concentration increased, mortality increased. The effective concentration of O_3 that increases the lung's susceptibility to infection is lowered when another pollutant, such as NO_2 or H_2SO_4, is combined with O_3. In some studies, additive effects were reported. These effects, increases in respiratory infection, are supported by many mechanistic studies discussed in this section. They indicate tha O_3 does effectively cause a reduction in a number of essential host defenses that would normally play a major role in fighting pulmonary infections. Since 1978, a number of new studies have continued to confirm these previous findings and improve the existing data base (Table 10-13).

When mice were exposed 4 hr to 392 to 1372 μg/m^3 (0.2 to 0.7 ppm) of O_3 and then challenged with virulent Klebsiella pneumoniae, a significant increase in mortality was noted at 785 μg/m^3 (0.4 ppm) O_3 (Bergers et al., 1982). Groups of 30 mice inhaled approximately 30, 100, and 300 bacteria/mouse. At 392 μg/m^3 (0.2 ppm) of O_3, the O_3 group showed an increase in mortality, but it was not significantly different from controls. At 785 μg/m^3

TABLE 10-13. EFFECTS OF OZONE ON HOST DEFENSE MECHANISMS: INTERACTIONS WITH INFECTIOUS AGENTS

Ozone concentration μg/m³	Ozone concentration ppm	Measurement[a] method	Exposure duration and protocol	Observed effects	Species	Reference
157	0.08	ND	3 hr	Increase in mortality to *Streptococcus pyogenes*.	Mouse	Coffin et al., 1968a
157-196	0.08, 0.1	CHEM	3 hr	Significant increase in mortality during O_2 exposure (*Streptococcus pyogenes*).	Mouse	Miller et al., 1978
196	0.1	CHEM	3 hr	Increased mortality to *Streptococcus pyogenes*.	Mouse	Ehrlich et al., 1977
196	0.1	UV	5 hr/day, 5 days/wk for 103 days	Increased susceptibility to bacterial infection (*Streptococcus pyogenes*).	Mouse	Aranyi et al., 1983
196, 588	0.1, 0.3	CHEM	3 hr	Exercise enhances mortality in infectivity model system.	Mouse	Illing et al., 1980
392-1372	0.2-0.7	G	3-4 hr	Significant increase in mortality following challenge with aerosol of *Klebsiella pneumoniae*. Effect seen at 0.4 ppm.	Mouse	Bergers et al., 1982
588	0.3	ND	3 hr/day for 2 days	Enhancement of severity of bacterial pneumonia (*Pasturella haemolytica*).	Sheep	Abraham et al., 1982
1372-1764	0.7-0.9	ND	3 hr	Increased susceptibility to infection (*Streptococcus pyogenes*).	Mouse	Coffin and Blommer, 1970
1960	1.0	CHEM	3 hr/day, 5 days/wk for 8 weeks	Increase in *Mycobacterium tuberculosis* lung titers.	Mouse	Thomas et al., 1981b
2940	1.5	ND	4 hr/day, 5 days/wk for 2 months	No effect on resistance to *Mycobacterium* tuberculosis.	Mouse	Thienes et al., 1965

[a] Measurement method: ND = not described; CHEM = gas phase chemiluminescence; UV = UV photometry; G = galvanic meter.

(0.4 ppm) of O_3 a nearly threefold lowering of the bacterial LD_{50} value computed from the three challenge doses of bacteria was found for the O_3-exposed group, indicating a significant increase in mortality. In the same study, the authors also found that 1372 $\mu g/m^3$ (0.7 ppm) of O_3 for 3 hr resulted in a decreased ability of the lung to clear (bactericidal) inhaled staphylococci. This finding is consistent with that of Goldstein et al. (1971b) and confirms previous studies reported by Miller and Ehrlich (1958) and Ehrlich (1963).

Chiappino and Vigiani (1982) also reported that O_3 (1.0 ppm) potentiated pulmonary infection in rats. In this study, the investigators wanted to know in what way O_3 modified the reactions to silica in specific pathogen-free (SPF) rats. Silica-treated animals were exposed to O_3 (8 hrs/day, 5 days a week for up to 1 year) and housed in either an SPF environment or in a conventional animal house, thus being exposed to the bacterial flora normally present there. The SPF-maintained, O_3-exposed rats showed a complete absence of saprophytes and pathogens in the lungs, whereas the microbial flora of the lungs of the conventionally kept rats, also exposed, consisted of staphylococci (2500 to 4000 per gram of tissue) and streptococci (300 to 800 per gram of tissue). The lungs of these rats showed bronchitis, purulent bronchiolitis, and foci of pneumonia. The exposure to O_3 did not have any effect on particle retention, nor did it modify the lungs' reaction to silica, but it did increase the animals' susceptibility to respiratory infections.

Changes in susceptibility to infection resulting from O_3 exposure have also been tested in sheep. In these studies, sheep were infected by an inoculation of Pasturella haemolytica either 2 days before being exposed to 588 $\mu g/m^3$ (0.3 ppm) of O_3 or 2 days after the O_3 exposure. In both cases, the O_3 exposure was for 3 hr/day for 2 days. Ozone enhanced the severity of the disease (volume of consolidated lung tissues), with the greatest effect seen when the O_3 insult followed the exposure to the bacteria (Abraham et al., 1982). Unfortunately, only a small number of animals were used in each O_3 treatment (n = 3).

Thomas et al. (1981b) studied the effects of single and multiple exposures to O_3 on the susceptibility of mice to experimental tuberculosis. Multiple exposures to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 3 hr/day, 5 days/week for up to 8 weeks, initiated 7 or 14 days after the infectious challenge with Mycobacterium tuberculosis H37RV, resulted in significantly increased bacterial lung titers, as compared with controls. Exposure to lower concentrations of

O_3 did not produce any significant effects. In an earlier study, Thienes et al. (1965) reported that exposure to 2940 µg/m^3 (1.5 ppm) of O_3 4 hr/day, 5 days/week for 2 months also did not alter the resistance of mice to M. tuberculosis H37RV, but he did not measure lung titers.

Table 10-14 summarizes a number of studies that used mixtures of pollutants in their exposure regimes. Ehrlich et al. (1979) and Ehrlich (1983) expanded the earlier 3-hr-exposure studies to determine the effects of longer periods of exposure to O_3 and NO_2 mixtures. In the earlier studies (Ehrlich et al., 1977), they reported that exposures to mixtures containing 196 to 980 µg/m^3 (0.1 to 0.5 ppm) of O_3 and 2920 to 9400 µg/m^3 (1.5 to 5 ppm) of NO_2 produced an additive effect expressed as an increased susceptibility to streptococcal pneumonia. In the later studies, mice were exposed 3 hr/day, 5 days/week for up to 6 months to mixtures of 196 µg/m^3 (0.1 ppm) of O_3 and 940 µg/m^3 (0.5 ppm) of NO_2 and challenged with bacterial aerosol. The 1- or 2-month exposure did not induce any significant changes in susceptibility to streptococcal infection. After 3 and 6 months of exposure the resistance to infection was significantly reduced. If the mice were re-exposed to the O_3 and NO_2 mixture after the infectious challenge, a significant increase in mortality rate could be detected 1 month earlier. The clearance rate of inhaled viable streptococci from the lungs also became significantly slower after the 3-month exposure to this oxidant mixture.

In more complex exposure studies, mice were exposed to a background concentration of 188 µg/m^3 (0.1 ppm) of NO_2 for 24 hr/day, 7 days/week with a superimposed 3-hr daily peak (5 days/week) containing a mixture of 196 µg/m^3 (0.1 ppm) of O_3 and 940 µg/m^3 (0.5 ppm) of NO_2. Mortality rates from streptococcal infection were not altered by 1- and 2-month exposures, but a marked, although not statistically significant ($p < 0.1$), increase was seen after a 6-month exposure.

The same laboratory (Aranyi et al., 1983) recently reported a study in which mice were exposed 5 hr daily, 5 days/week up to 103 days to O_3 and a mixture of O_3, SO_2, and $(NH_4)_2SO_4$. The concentrations were 200 µg/m^3 of O_3, 13.2 mg/m^3 of SO_2, and 1.04 mg/m^3 of $(NH_4)_2SO_4$. Both groups showed a highly significant overall increase in mortality, compared to control mice exposed to filtered air. However, the two exposure groups did not differ, indicating that O_3 was the major constituent of the mixture affecting the host's susceptibility to infection. These investigators also measured a number of specific

TABLE 10-14. EFFECTS OF OZONE ON HOST DEFENSE MECHANISMS: MIXTURES

Ozone concentration		Pollutant	Measurement[a] method	Exposure duration and protocol	Observed effects[b]	Species	Reference
$\mu g/m^3$	ppm						
98 3760	0.05	O_3 + NO_2	CHEM	3 hr	Exposure to mixtures caused synergistic effect after multiple exposures.	Mouse	Ehrlich et al., 1977
98-196 100-400 1500	0.05-0.1	O_3 + NO_2 + $ZnSO_4$	CHEM	3 hr	Additive effect of pollutant mixtures with infectivity model.	Mouse	Ehrlich, 1983
196 241-483	0.1	O_3 + H_2SO_4	CHEM	3 hr	Increased susceptibility to Streptococcus pyogenes.	Mouse	Grose et al., 1982
196 900	0.1	O_3 + H_2SO_4	CHEM	3 hr + 2 hr	Sequential exposure resulted in significant increase in respiratory infection. Neither alone produced a significant effect.	Mouse	Gardner et al., 1977
196 1090	0.1	O_3 + H_2SO_4	CHEM	3 hr + 2 hr	Sequential exposure resulted in significant reduction in ciliary beating activity.	Hamster	Grose et al., 1980
196 980	0.1	O_3 + NO_2	CHEM	3 months	Significant decrease in viability of alveolar macrophages.	Mouse	Ehrlich, 1980
196 980	0.1	O_3 + NO_2	CHEM	1-6 months	At 3 and 6 months, susceptibility to pulmonary infection increased significantly. Delayed clearance rate.	Mouse	Ehrlich, 1980
196 13200 1040	0.1	O_3 + SO_2 + $(NH_4)_2SO_4$	UV	5 hr/day, 5 days/wk for 103 days	Highly significant increase in susceptibility to infection. Effects attributed to O_3. Increased bactericidal rate. Mixture showed greater growth inhibition in leukemia target cells and an increase in blastogenic response to PHA, Con-A, and alloantigens.	Mouse	Aranyi et al., 1983

TABLE 10-14. EFFECTS OF OZONE ON HOST DEFENSE MECHANISMS: MIXTURES (continued)

Ozone concentration μg/m³	ppm	Pollutant	Measurement[a] method	Exposure duration and protocol	Observed effects[b]	Species	Reference
216-784 3760-13720	0.11-0.4 2-7.3	O_3 + NO_2	A	17 hr before bacteria or 4 hr after bacterial exposure	Physical removal of bacteria not affected. Bactericidal activity reduced at higher concentrations.	Mouse	Goldstein, E., et al., 1974
980 11-3000	0.5	O_3 + H_2SO_4	UV	3 and 14 days	Significant increase in glycoprotein secretion; synergism reported; effect reversible in clean air.	Rat	Last et al., 1978
1568 3500 3500 3500	0.8	O_3 + $Fe_2(SO_4)_2$ + H_2SO_4 + $(NH_4)_2SO_4$	UV	4 hr	Exposure to mixtures produced same effect as exposure to O_3 alone.	Rat	Phalen et al., 1980

[a] Measurement method: CHEM = gas phase chemiluminescence; UV = UV photometry; A = amperometric.

[b] Abbreviations used: PHA = phytohemagglutinin; Con-A = concanavalin-A

host defenses to determine if host response to the mixtures was significantly different from that of the controls or of the O_3-only groups. Neither the total number, differential, nor the ATP levels of macrophages differed from controls in either group, but the complex mixture did produce a significant increase in bactericidal activity over the O_3-alone and the control animals.

Previous studies (Gardner et al., 1977) indicated that a sequential exposure to O_3 followed by H_2SO_4 significantly increased streptococcal pneumonia-induced mortality rates in mice. Ozone and H_2SO_4 had an additive effect when exposed in this sequence. However, the reverse sequence did not affect incidence of mortality. Grose et al. (1982) expanded these studies and showed that a 3-hr exposure to the combined aerosol of 196 $\mu g/m^3$ (0.1 ppm) of O_3 and 483 or 241 $\mu g/m^3$ H_2SO_4 also significantly increased the percent mortality, as compared to control.

The effects of exercise on the response to low levels of O_3 were also studied by using the infectivity model. Mice were exposed to 196 $\mu g/m^3$ (0.1 ppm) of O_3 and 588 $\mu g/m^3$ (0.3 ppm) of O_3 for 3 hr while exercising. Each exposure level yielded mortality rates that were significantly higher than those observed in the O_3 group that was not exercised (Illing et al., 1980). Such activity could change pulmonary dosimetry, thus increasing the amount of O_3 reaching the respiratory system. Thus, such studies clearly demonstrate that the activity level of the exposed subjects is an important concomitant variable influencing the determination of the lowest effective concentration of the pollutant.

10.3.4.4 Immunology. In addition to the above nonspecific, nonselective mechanisms of pulmonary defense, the respiratory system also is provided with specific, immunologic mechanisms, which can be activated by inhaled antigens. There are two types of immune mechanisms: antibody-humoral-mediated and cell-mediated. Both serve to protect the respiratory tract against inhaled pathogens. Much less information is available on how O_3 reacts with these immunological defenses than is known about the macrophage system (see Table 10-15).

The effects of 2900 $\mu g/m^3$ (1.48 ppm) of O_3 for 3 hr on cell-mediated immune response were studied by Thomas et al. (1981b), who determined the cutaneous delayed hypersensitivity reaction to purified protein derivative (PPD), expressed as the diameter of erythemas. In the guinea pigs infected

TABLE 10-15. EFFECTS OF OZONE ON HOST DEFENSE MECHANISMS: IMMUNOLOGY

Ozone concentration		Measurement[a] method	Exposure duration and protocol	Observed effects[b]	Species	Reference
μg/m³	ppm					
196	0.1	UV	5 hr/day, 5 days/wk for 90 days	Significant suppression in blastogenesis to T-cell mitogen, PHA, and Con-A. No effect on B-cell mitogen, LPS, or alloantigen of splenic lymphocytes.	Mouse	Aranyi et al., 1983
980, 2940	0.5, 1.5	ND	4 hr	Attempt to increase immune activity with drug Levamisole failed.	Mouse	Goldstein et al., 1978a
980, 1568	0.5, 0.8	Mast	Continuous 3-4 days	Increase in number of IgE- and IgA-containing cells in the lung, resulting in an increase in anaphylactic sensitivity.	Mouse	Osebold et al., 1979, 1980 Gershwin et al., 1981
980-2900	0.5-1.48	CHEM	3 hr	Depressed cell-mediated immunity. No effect at 0.5 ppm for 5 days. Hemagglutination antibody titers increased over control.	Guinea pig	Thomas et al., 1981b
1150	0.59	ND	36 days	Impaired resistance to toxin stress. Immunosuppression.	Mouse	Campbell and Hilsenroth, 1976

[a] Measurement method: ND = not described; CHEM = gas phase chemiluminescence; UV = UV photometry; Mast = Mast meter.

[b] Abbreviations used: PHA = phytohemagglutinin; con-A = concanavalin-A; LPS = lipopolysaccharide; IgE = immunoglobulin-E; IgA = immunoglobulin-A.

with Mycobacterium tuberculosis, the cutaneous sensitivity to PPD was significantly affected by O_3. The diameters of the erythemas from the O_3-exposed animals were significantly smaller during the 4 to 7 weeks after the infectious challenge, indicating depressed cell-mediated immune response. Exposure to 980 $\mu g/m^3$ (0.5 ppm) of O_3 had no effect.

The systemic immune system was studied by Aranyi et al. (1983), who observed the blastogenic response of splenic lymphocytes to mitogens and alloantigens and plaque-forming cells' response to sheep red blood cells after a chronic exposure (200 $\mu g/m^3$ of O_3 5 hr/day, 5 days/week for 90 days). No alteration in the response to alloantigens or the B-cell mitogen lipopolysaccharide (LPS) was noted, but a statistically significant suppression in blastogenesis to the T-cell mitogens (PHA and con-A) was detected. The authors suggested this indicated that the cellular mechanisms for recognition and proliferation to LPS and alloantigens were intact, but O_3 might have been interfering with the cellular response to PHA and con-A through alterations in cell surface receptors or the binding of specific mitogens to them. Ozone exposure enhances peritoneal macrophage cytostasis to tumor target cells. There was no effect on the ability of splenic lymphocytes to produce antibodies against injected antigen (red blood cells).

Campbell and Hilsenroth (1976) used a toxoid immunization-toxin challenge approach to determine if continuous exposure to 1150 $\mu g/m^3$ (0.59 ppm) of O_3 for 36 days impaired resistance to a toxin stress. Mice were immunized with tetanus toxoid on the fifth day of O_3 exposure and challenged with the tetanus toxin on day 27. Compared with controls, the O_3-exposed animals had greater mortality and morbidity following the challenge. The authors suggested that the effect was due to immunosuppression.

Because the data indicate that O_3 can alter the functioning of pulmonary macrophages, Goldstein et al. (1978a) tried to counteract this effect by using a known immunologic stimulant, Levamisole, which protects rodents against systemic infections of staphylococci and streptococci. The purpose was to determine if this drug might repair this dysfunction and improve the bactericidal activity of the macrophage. In this study, two concentrations were tested, 2940 and 980 $\mu g/m^3$ (0.5 and 1.5 ppm) of O_3 for 4 hr. In no case did Levamisole improve the bactericidal activity of the O_3-exposed macrophages. The cells still failed to respond normally.

The possibility that O_3 may be responsible for the enhancement of allergic sensitization has important implications for human health effects. Gershwin et al. (1981) reported that O_3 (0.8 and 0.5 ppm for 4 days) exposure caused a thirty-fourfold increase in the number of IgE-containing cells in the lungs of mice. In general, the number of IgE-containing cells correlated positively with levels of anaphylactic sensitivity. Oxidant damage (0.5 to 0.8 ppm for 4 days) also causes an increase in IgA-containing cells in the lungs and a rise in IgA content in respiratory secretions and accumulation of lymphoid tissue along the airways (Osebold et al., 1979). These authors showed that a significant increase in anaphylactic sensitivity occurred when antigen-stimulated and O_3-exposed animals were compared to controls (Osebold et al., 1980). Significantly greater numbers of animals were allergic in experimental groups which O_3 exposure ranged from 0.8 ppm to 0.5 ppm for 3 days. Further studies are needed to determine the threshold level of these effects.

10.3.5 Tolerance

Acclimatization, whether it be a long-term or a moment-to-moment response of the organism to a changing environment, has been a phenomenon of major interest to toxicologists for years. Tolerance, in the broadest sense of the word, may be viewed as a special form of acclimatization in which exposure to a chemical agent results in increased resistance, either partial or complete, to the toxicant (Hammond and Beliles, 1980). Often the terms tolerance and resistance are used interchangeably. The word, tolerance, is primarily used when the observed decrease in susceptibility occurs in an individual organism as a result of its own previous or continuing exposure to the particular toxicant or to some other related stimulus. Resistance generally refers to relative insusceptibility that is genetically determined (Hayes, 1975).

A third term, adaptation, has been widely used primarily to describe the diminution of response seen in human subjects who have undergone repeated O_3 exposure (Chapter 11, Section 3). This adaptation might well result from a different biologic process than that referred to in the various animal tolerance studies. It is not yet known whether the laboratory animal develops adaptive responses similar to those seen in humans (i.e., respiratory mechanical functions, symptoms of respiratory irritation, and airway reactivity). Thus, to date, the precise distinction or definition of these two forms, tolerance and adaptation, are not yet fully understood in any concise manner.

Further research is needed to focus on the specific structural/functional response being addressed in each specific experimental situation and to relate this to the exposure concentration and profiles of O_3. An attempt to relate the modified responses seen in animals to what has been described in human subjects will be made in Chapter 13.

In animal oxidant toxicity studies, the term tolerance classically is defined as the phenomenon wherein a previous exposure to a nonlethal dose of O_3 will provide some protection against a subsequent exposure to a dose of O_3 expected to be lethal. The degree of tolerance depends considerably on the duration of the exposure and the concentration. Tolerance occurs rapidly and can persist for several weeks (Mustafa and Tierney, 1978). The term tolerance should not be considered to indicate complete or absolute protection, because continuing injury does occur and can eventually lead to nonreversible morphological changes. This protective phenomenon seen with oxidants was originally described by Gildemeister (1921) in cats undergoing exposure to phosgene.

In the typical experiment, animals are pre-exposed to a lower concentration of O_3 and then challenged at a later time to a higher concentration. As early as 1956, Stokinger et al. presented data clearly indicating that an animal could also become tolerant to the lethal effects of O_3. Such tolerance has also been reported by many investigators, including Matzen (1957a), Mendenhall and Stokinger (1959), Henschler (1960), and Fairchild (1967). The observation of this tolerance phenomenon in experimentally exposed animals has led to the speculation that it may also be a mechanism for protecting environmentally exposed humans.

The previous criteria document for O_3 and other photochemical oxidants cited various studies (Table 10-16) that examined O_3 tolerance and presented some evidence indicating possible mechanisms of action. Review of these earlier data reveals that pre-exposure to a certain concentration of O_3 can protect test animals from the acute lethal effects of a second exposure to O_3. This protection has been attributed to a significant reduction in pulmonary edema in the pre-exposed animals. Table 10-16 lists the key studies on O_3.

Because O_3 has a marked proclivity to reduce the ability of alveolar macrophages to function, studies were conducted to determine how the pulmonary defense system in tolerant animals compared with naive animals. With the bacterial infectivity model (Section 10.3.4.3), the pre-exposed (tolerant) animals were only partially protected from the aerosol infectious challenge

TABLE 10-16. TOLERANCE TO OZONE

Ozone (μg/m³) pre-exposure	Ozone (ppm) pre-exposure	Length of pre-exposure	Ozone (μg/m³) after latent period	Ozone (ppm) after latent period	Length of exposure after latent period	Observed effect(s)	Species	Reference
196-1960	0.1-1.0	3 hr	196-1960	0.1-1.0	3 hr	Lower mortality for pre-exposed mice than mice receiving only one O_3 dose. Complete tolerance was not evident.	Mouse	Gardner and Graham, 1977
196	0.1	30 min	196	0.1	30 min	Tolerance exhibited in the lungs' periphery, as measured by collateral resistance. Response $\leq$ controls in tolerant animals.	Dog	Gertner et al., 1983b
490	0.25	6 hr	1966	1	6 hr	No tolerance to edema unless pretreated with methylprednisolone.	Rat	Alpert et al., 1971a
980	0.5	6 hr				Edema as measured by recovery of ^{132}I in pulmonary lavage fluid.		
588	0.3	1 hr	39,200	20	2 hr	Tolerance to edema effects of O_3 did not develop in thymectomized animals but developed in sham-operated animals, indicating the thymus may be involved in tolerance.	Mouse	Gregory et al., 1967
588	0.3	3 hr	588	0.3	3 hr	20% lower mortality for pre-exposed mice than mice receiving only one O_3 dose. Partial tolerance probably due to inhibition of edemagenesis.	Mouse	Coffin and Gardner, 1972a
588-980	0.3-0.5	4 days	980 1372 1960	0.5 0.7 1.0	1, 2, 4 days	Lack of total protection indicated by increased numbers of type 2 cells.	Rat	Evans et al., 1971, 1976a,b
980-1960	0.5, 1.0	3 hr	43,120	22	3 hr	With unilateral lung exposure technique, tolerance to edema a local effect and seen only in the pre-exposed lung.	Rabbit	Alpert et al., 1971b Alpert and Lewis, 1971

TABLE 10-16. TOLERANCE TO OZONE (continued)

Ozone (μg/m³) pre-exposure	Ozone (ppm) pre-exposure	Length of pre-exposure	Ozone (μg/m³) after latent period	Ozone (ppm) after latent period	Length of exposure after latent period	Observed effect(s)	Species	Reference
980	0.5	3 hr	5880 or	3 and 22	3 hr	With unilateral lung exposure technique, tolerance developed only to pulmonary edema. No tolerance to the chemotaxis of polymorphonuclear leukocytes or decreased lysosomal hydrolase enzyme activity.	Rabbit	Gardner et al., 1972
1470	0.75	3 days	7840	4.0	8 hr	A smaller decrease in activities of glutathione peroxidase, glutathione reductase, glucose-6-phosphate dehydrogenase and levels of reduced glutathione in lungs of tolerant animals, as compared to nontolerant animals.	Rat	Chow, 1976 Chow et al., 1976b
1600	0.8	4 hr	2352	1.2	4 hr	Pre-exposure to O_3 caused complete tolerance to delay in mucociliary clearance at 3 days, but not 13 days.	Rat	Frager et al., 1979
1960	1	1 hr	ND	ND	ND	All animals X-irradiated to 800 R. 60% of O_3-pre-exposed mice survived. 100% of controls died.	Mouse	Hattori et al., 1963
1960	1	1 hr	3920	2	1 hr	Tolerance to allergic response to inhaled acetylcholine.	Guinea pig	Matsumura et al., 1972

ND = not described.

(Coffin and Gardner, 1972a; Gardner and Graham, 1977). The partial protection was evident at O_3 concentrations that had been shown to be edemagenic; however, at the lowest concentration, 200 μg/m^3 (0.10 ppm) of O_3, there was no significant difference imparted by the use of the tolerant-eliciting exposure. The data suggest that at the higher concentrations (> 0.3 ppm), pre-exposure prevented edema, which prophylactically aided the animals' defenses against the inhaled microorganisms. Because the protection was only fractional and did not occur at the lowest level, however, O_3 still suppressed specific body defenses that were not protected by the phenomenon of tolerance.

To further investigate this hypothesis (Alpert and Lewis, 1971; Gardner et al., 1972), studies were conducted to evaluate the effects of tolerance at the cellular level. These studies indicated that the initial O_3 exposure did induce tolerance against pulmonary edema in the exposed lung; however, there was no protection afforded against the cytotoxic effects of O_3 at the cellular level. The cytological toxic injuries measured in this study (including significant reductions in enzymatic activities of macrophages and an increase in inflammation, as measured by the presence of polymorphonuclear leukocytes--PMN) showed that there was no protection against these cellular defense mechanisms.

Evans et al. (1971, 1976b) also measured tolerance by studying the kinetics of alveolar cell division in rats during a period of exposure to an elevated O_3 concentration of 980 or 1372 μg/m^3 (0.50 or 0.70 ppm, up to four days) that followed initial exposure at a lower concentration of 686 μg/m^3 (0.35 ppm) for four days. Tolerance in this case was the ability of type 1 cells to withstand a second exposure without any increase in the number of type 2 cells, which would indicate a lack of complete tolerance. Similar to the host defense studies cited above, these investigations showed that tolerance to the initial concentration of O_3 did not ensure complete protection against re-exposure to the higher O_3 concentration.

Attempts have been made to explain tolerance by examining the morphological changes that occur due to repeated exposures to O_3. In these studies the investigators attempt to assess various structural responses with various exposure profiles and concentrations. Dungworth et al. (1975b) and Castleman et al. (1980) studied the repair rate of O_3 damage as indicated by DNA synthesis. These effects are fully described in Section 10.3.1.2, and they indicate that with continuous exposure to O_3, the lung attempts to initiate the repair of the O_3 lesion, resulting in somewhat reduced or less than expected total damage. These authors suggest that this is an indication that although the damage is continuing, it is at a lower rate, and they refer to this phenomenon as adaptation.

It has been suggested that the tolerance to edema seen in animal studies can be explained through the indirect evidence that more resistant cells, such as type 2 cells, may replace the more sensitive, older type 1 cells, or that the type 2 cells may transform to younger, more resistant cells of the same type (Mustafa and Tierney, 1978). A number of workers have reported that the younger type 1 cells are relatively more resistant to the subsequent toxicity of O_3 (Evans et al., 1976a; Dungworth et al., 1975a; Schwartz et al., 1976). Thus, there is also the possibility that this reparative-proliferative response relines the airway epithelium with cells that have a biochemical armamentarium more resistant to oxidative stress (Mustafa et al., 1977; Mustafa and Lee, 1976).

Another suggestion is that with O_3, exposure there is cellular accumulation within the airways resulting in mounds of cells in the terminal bronchioles that may cause considerable narrowing of the airways (Berliner et al., 1978). As the airways become more obstructed, the O_3 molecules are less likely to penetrate to lumen. This may result in a filtering system that removes the O_3 from the inhaled air before it reaches the alveoli.

More recently, there have been additional studies examining the protective effects of this tolerance phenomenon in animals. Frager et al. (1979) studied the possibility of tolerance to O_3 in mucociliary clearance. Exposure of rats to 1.2 ppm of O_3 following particle deposition caused a substantial delay in mucociliary clearance. This O_3 effect could be eliminated by a pre-exposure to 1600 $\mu g/m^3$ (0.80 ppm) of O_3 for 4 hr, 3 days before the deposition of the particles. Thus, the pre-exposure provided complete protection against the higher O_3 level that lasted for about one week. The possible mechanism for this protection could be a thickening of the mucus layer, which would offer the epithelium an extra physical barrier against O_3. As the secretion returns to normal, the protection is lost. The authors suggested that another possible mechanism for this protection involves the ciliated cells and their cilia. In this case, the protection could result from either the formation of intermediate cilia (Hilding and Hilding, 1966) or the occurrence of some other temporary change in the regenerating ciliated cell.

Tolerance to O_3 has also been studied by using a variety of biochemical indicators to measure the extent to which a pre-exposure to O_3 protects or reduces the host response to a subsequent exposure. Chow et al. (1976a,b) compared a variety of metabolic activities of the lung immediately after an initial 3-day continuous exposure to 1600 $\mu g/m^3$ (0.80 ppm) of O_3 with the response after subsequent re-exposure. At 6, 13, and 27 days after the pre-exposure ended, the animals were once again treated to the same exposure routine. If tolerant, the animals should have shown a diminution of response. However, the re-exposed rats responded similarly to those animals tested after the initial exposure. The lungs of the naive animals had equivalently higher activities of glutathione peroxidase, glutathione reductase, glucose-6-phosphate dehydrogenase and higher levels of nonprotein sulfhydryl than controls and were comparable to the animals that were exposed and tested immediately after the initial exposure. The authors state that this indicated that by the time recovery from the pre-exposure is complete, the lung is as susceptible to the re-exposure injury as a lung that has never been exposed.

A number of biochemical effects of O_3 gradually subside in intensity despite continued exposure to the gas. An example is prolyl hydroxylase, a key enzyme in collagen synthesis that serves as a sensitive indicator of disturbances in collagen metabolism. The increase in superoxide anion caused by O_3 stimulates collagen synthesis. This is reflected in an increase in prolyl hydroxylase activity. Bhatnagar et al. (1983) have shown that there is also an increase in superoxide dismutase, which quenches free radicals, thereby restricting hydroxylase activity and collagen formation.

Gertner et al. (1983b) presented data showing that the development of adaptation and tolerance is rapid and mediated through the vagus nerve. These investigators used a bronchoscope to study the response of the periphery of the lung to O_3 exposure. Measurements of collateral resistance (Rcoll) were used to monitor the response to O_3. During a 30-min exposure to 0.1 ppm, the Rcoll increased 31.5 percent within 2 min and then gradually decreased to control level in spite of continual exposure to O_3. Fifteen minutes after the O_3 exposure ceased, the Rcoll returned to normal. Subsequent exposure to 0.1 ppm of O_3 did not increase Rcoll, indicating that some protection existed. These investigators have tried to distinguish between the terms adaptation and tolerance based on these studies. They used adaptation to describe the pattern of changes that occur during continuous exposure to O_3 and the term tolerance to describe resistance to subsequent O_3 exposure.

Thus, the available evidence from animal studies suggests that tolerance does not develop to all forms of lung injury. The protection described against edemagenic effects of O_3 does not appear to offer complete protection, as illustrated by the following examples.

1. There is no tolerance (i.e., no protection occurs) on the part of the specific pulmonary defense mechanisms against bacterial infection below the edemagenic concentration; whereas above the edema-inducing concentration the effect of tolerance (i.e., inhibition of pulmonary edema), can lower the expected mortality rate because the animals do not have to cope with the additional burden of the edema fluid.
2. Specific cellular functions of the alveolar macrophage (i.e., enzyme activity) are incapable of being protected by tolerance.
3. Various biochemical responses were found in both naive and pre-exposed animals.
4. Tolerance fails to inhibit the influx of polymorphonuclear leukocytes into the airway.

This last finding is interesting in the face of effective tolerance for edema production. This suggests that the chemotactic effect of O_3 may be separable from the edemagenic effect. This may explain why chronic morphological changes in the lung may occur after long-term exposure, even though there may not be any edema.

The possible explanations for this tolerance phenomenon have been proposed by Mustafa and Tierney (1978). The primary mechanism of tolerance may not be due to hormonal or neurogenic pathways, because unilateral lung exposure does not result in tolerance of the nonpre-exposed lung (Gardner et al., 1972, Alpert and Lewis, 1971). But it should be noted that Gertner et al. (1983b) have evidence that local tolerance may involve a neural reflex. Changes in Rcoll may be mediated through the vagus nerve. After bilateral cervical vagotomy, the resistance did not increase during O_3 exposure but did after challenging with histamine, indicating that the parasympathetic system may play a role in response to O_3 in the periphery of the lung. There is some evidence that O_3 may cause a decrease in cellular sensitivity, an increased capacity to destroy the test chemical, or the repair of the injured tissue (Mustafa and Tierney, 1978). In addition, O_3 could possibly cause anatomic changes, such as an increase in mucus thickness, that may, in effect, prevent O_3 from reaching the gas-exchange areas of the lung.

It should be mentioned that the term tolerance carries with it the connotation that some form of an insult and/or damage has occurred and there has been an overt response at the structural and/or functional level. The response may be attenuated or undetectable, but the basis for the establishment of the tolerance still persists. It is possible that the cost for tolerance may be minor, such as a slight increase in mucus secretion; however, one must also be aware that changes in response to diverse kinds of insults to a host's system, such as the immune system, are adaptations with great potential for possible future harm.

10.4 EXTRAPULMONARY EFFECTS OF OZONE

10.4.1 Central Nervous System and Behavioral Effects

Despite reports of headache, dizziness, and irritation of the nose, throat, and chest in humans exposed to O_3 (see Chapter 11), and the possible implications of these and other symptoms as indications of low-level O_3 effects, few recent reports were found on behavioral and central nervous system (CNS) effects of O_3 exposure in animals. Table 10-17 summarizes studies on avoidance and conditioned behavior, motor activity, and CNS effects.

Early investigations have reported effects of O_3 on behavior patterns in animals. Peterson and Andrews (1963) attempted to characterize the avoidance behavior of mice to O_3 by measuring their reaction to a 30-min exposure on one side of an annular plastic mouse chamber. A concentration-related avoidance of the O_3 side was reported at 1176 to 16,660 $\mu g/m^3$ (0.60 to 8.50 ppm) of O_3. However, the study had serious shortcomings, including a lack of position-reversal controls (Wood, 1979), considerable intersubject variability, and other design flaws (Doty, 1975). Tepper et al. (1983) expanded on the design by using inhalant escape behavior to assess directly the aversive properties of O_3. Mice were individually exposed to O_3 for a maximum of 60 sec, followed by a chamber washout period of 60 sec. The animals could terminate exposure by poking their noses into only one of two brass conical recesses containing a photobeam. The delivery of 980 $\mu g/m^3$ (0.50 ppm) of O_3 was reliably turned off for a greater proportion of experimental trials, compared to control trials with filtered air. At 19,600 $\mu g/m^3$ (10 ppm) of O_3, all animals turned off 100 percent of the trials with an average latency of approximately 10 sec.

TABLE 10-17. CENTRAL NERVOUS SYSTEM AND BEHAVIORAL EFFECTS OF OZONE

Ozone concentration µg/m^3	Ozone concentration ppm	Measurement method[a,b]	Exposure duration and protocol	Observed effects(s)[c]	Species	Reference
110	0.056	d	93 days, continuous	No overt behavioral changes. Cholinesterase activity inhibited at 75 days of exposure, returning to control levels 12 days after termination of exposure.	Rat	Eglite, 1968
98-1960	0.05-1.0	MAST	45 min	Motor activity progressively decreased with increasing O_3 concentrations up to 0.5 ppm. Slight increase in frequency of 3-min intervals without motor activity.	Rat	Konigsberg and Bachman, 1970
196-3920	0.1-2.0	CHEM	6 hr	Linear and/or monotonic decreases in operant behavior during exposure.	Rat	Weiss et al., 1981
235-1960	0.12-1.0	CHEM	6 hr	Wheel running activity decreased monotonically with increasing O_3 concentration. Components of running were differentially affected at low vs. high O_3 concentrations.	Rat	Tepper et al., 1982
392-980	0.2-0.5	NBKI	6 hr	Wheel running activity decreased 50%.	Mouse	Murphy et al., 1964
588-1372	0.3, 0.7	MAST	7 days, continuous	Running activity decreased 60% during first 2 days, returning to control levels during the next 5 days of exposure; running activity decreased 20% when 0.3 ppm exposure was followed immediately by 0.7 ppm O_3 exposure. Adaptation with continued exposure was apparent.		
980-19600	0.5-10.0	CHEM	60 s	Exposure terminated by nose pokes with increasing frequency as O_3 concentration increased.	Mouse	Tepper et al., 1983
980	0.5	ND	30 min	Elevation of simple and choice reactive time.	Nonhuman primate	Reynolds and Chaffee, 1970

TABLE 10-17. CENTRAL NERVOUS SYSTEM AND BEHAVIORAL EFFECTS OF OZONE (continued)

Ozone concentration μg/m³	ppm	Measurement method[a,b]	Exposure duration and protocol	Observed effects(s)[c]	Species	Reference
980-1960	0.5, 1.0	NBKI	1 hr	Evoked response to light flashes in the visual cortex and superior colliculus decreased after exposure.	Rat	Xintaras et al., 1966
1176-16,660	0.6-8.5	e	30 min	Avoidance behavior increased with increasing O_3 concentration.	Mouse	Peterson and Andrews, 1963
1960	1.0	MAST NBKI	7 days, continuous	Reduction in wheel running activity; no effect of Vitamin E deficiency or supplementation.	Rat	Fletcher and Tappel, 1973
1960-5880	1-3	ND	18 months, 8 hr/day	COMT activity decreased at 2 ppm, MAO activity increased at 1 ppm only.	Dog	Trams et al., 1972
1960	1		18 months; 8, 6, 24 hr/day	COMT activity decreased as the daily exposure increased from 8 to 24 hr. MAO activity increased at 8 and 16 hr/day and decreased at 24 hr/day.		
1960-5880	1-3	ND	18 months, 8 hr/day	Alterations in EEG patterns after 9 months, but not after 18 months of exposure.	Dog	Johnson et al., 1974

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[a] Measurement method: MAST = KI-coulometric (Mast meter); CHEM = gas phase chemiluminescence; NBKI = neutral buffered potassium iodide; ND = not described.

[b] Calibration method: NBKI = neutral buffered potassium iodide.

[c] Abbreviations used: COMT = catechol-o-methyltransferase; MAO = monamine oxidase; EEG = electroencephalogram

[d] Spectrophotometric method with dihydroacridine.

[e] KI titration with sodium thiosulfate.

Studies by Murphy et al. (1964) demonstrated that wheel-running activity decreased by approximately 50 percent when mice were exposed to 392 to 980 μg/m^3 (0.20 to 0.50 ppm) of O_3 for 6 hr and decreased to 60 percent of pre-exposure values during the first 2 days of continuous exposure to 588 μg/m^3 (0.30 ppm) of O_3. Running activity gradually returned to pre-exposure values during the next 5 days of continuous exposure to 588 μg/m^3 (0.30 ppm) of O_3. If the same mice were subsequently exposed to 1372 μg/m^3 (0.70 ppm) of O_3 for an additional 7 days, running activity was depressed to 20 percent of pre-exposure values. Partial recovery was described during the final days of exposure to 1372 μg/m^3 (0.70 ppm), and complete recovery occurred several days after exposure was terminated. However, partial tolerance was seen when the air-control mice were subsequently exposed to 392 μg/m^3 (0.20 ppm) of O_3 for 7 days. Konigsberg and Bachman (1970) used a capacitance-sensing device to record the motor activity of rats during a 45-min exposure to 98, 196, 392, 980, and 1960 μg/m^3 (0.05, 0.10, 0.20, 0.50, and 1.0 ppm) of O_3. Compared with control rats, motor activity following O_3 exposure progressively decreased with increasing O_3 concentrations up to 980 μg/m^3 (0.50 ppm). No greater reduction was obtained at 1960 μg/m^3 (1.0 ppm). In addition, the frequency of 3-min intervals without measurable motor activity tended to increase slightly (from 1 to 1.25 to approximately 3) with increasing O_3 concentration.

A detailed microanalysis of motor activity was undertaken by Tepper et al. (1982), who exposed rats for 6-hr periods during the nocturnal phase of their light-dark cycle to 235, 490, 980, and 1960 μg/m^3 (0.12, 0.25, 0.50 and 1.0 ppm) of O_3. The 3 days preceding an exposure were used for control observations to measure running activity for each rat in a wheel attached to the home cage. Decreases in wheel running activity occurred at 235 μg/m^3 (0.12 ppm) and progressively greater decreases in wheel running activity occurred with increasing O_3 concentration. An analysis of the running behavior showed that the components of running were differentially affected by O_3. An increase in the time interval between running bursts primarily accounted for the decreased motor activity at the low (235 μg/m^3, 0.12 ppm) O_3 concentration. Postexposure increases in wheel running were seen following this low O_3 concentration. At higher O_3 concentrations (>490 μg/m^3, 0.25 ppm), an increase in the time per wheel revolution, a decrease in the burst length as well as the extended time interval between bursts contributed to the reduced motor activity. These higher concentrations also caused a decrease in performance compared to control for several hours after exposure was terminated.

Effects of O_3 on behavior were further investigated by Weiss et al. (1981) in their studies on the operant behavior of rats during O_3 exposure. The term operant refers to learned behaviors that are controlled by subsequent events such as food or shock delivery. In this case, rats were trained to perform a bar-pressing response maintained by a reward with food pellets delivered according to a 5-min fixed-interval reinforcement schedule. The rats were exposed for 6 hr to O_3 concentrations from 196 to 3920 $\mu g/m^3$ (0.10 to 2.0 ppm), with at least 6 days separating successive exposures. Two groups of rats were tested, one beginning in the morning and the other in the mid afternoon. Ozone-induced decreases were linear from 196 to 2744 $\mu g/m^3$ (0.10 to 1.40 ppm) for the first group; for the second, the decreases were generally monotonic from 196 to 3920 $\mu g/m^3$ (0.10 to 2.0 ppm). Analysis of the distribution of responses during the various O_3 exposures indicated concentration-related decreases arose mainly from the later portions of the sessions and that the onset of the decline in response occurred earlier at the higher O_3 concentrations. In contrast to other types of toxicants, O_3 did not disrupt the temporal pattern that characterized response during each fixed-interval presentation. Based on the sedentary nature of the task, the authors suggested that the inclination to respond rather than the physiological capacity to respond was impaired.

Kulle and Cooper (1975) studied the effects of O_3 on the electrical activity of the nasopalatine nerve in rats. Ozone exposure to 9800 $\mu g/m^3$ (5 ppm) for 1 hr produced an increase in nasopalatine nerve response (action potential frequency) to amyl alcohol, suggesting that the nerve receptors were made more sensitive by prior exposure to O_3. One-hour air perfusion following the O_3 exposure reduced the neural response to amyl alcohol, but not to pre-exposure levels. The nasopalatine nerve is a branch of the trigeminal nerve which responds to airborne chemical irritants. Because most irritants, including O_3, also have odorant properties and, therefore, stimulate both trigeminal and olfactory receptors in the nasal mucosa, it is difficult to distinguish an irritant response from an odor response as the mechanism for behavioral effects in laboratory animals.

Effects of O_3 on the CNS have been reported. Trams et al. (1972) measured biochemical changes in the cerebral cortex of dogs exposed for 18 months to 1960, 3920, or 5880 $\mu g/m^3$ (1, 2, or 3 ppm) of O_3. In 8 hr/day exposures, reported decreases (35 percent) in the catecholamines norepinephrine and epinephrine were not statistically significant, although O_3 exposure at 3920 µg/m^3 (2 ppm) caused a statistically significant decrease in catechol-o-methyl-transferase (COMT) activity. In contrast, monamine oxidase (MAO) activity was significantly elevated at 1960 µg/m^3 (1 ppm) of O_3, but not at 3920 or 5880 µg/m^3 (2 or 3 ppm) of O_3. Increasing daily exposures to 1960 µg/m^3 (1 ppm) from 8 to 24 hr/day caused a significant decrease in COMT activity, but MAO activity increased at 8 and 16 hr/day but decreased at 24 hr/day. Concurrently, Johnson et al. (1974) measured electroencephalographic (EEG) patterns in the same dogs and noted alterations in EEG patterns after 9 months of exposure to 1960 to 5800 µg/m^3 (1 to 3 ppm) of O_3, but not after 18 months of exposure. The authors noted that it was difficult to correlate the observed EEG changes with the alterations of metabolic balance described. Furthermore, it was even more difficult to assess the metabolic and physiologic significance of the changes without more information about chronic O_3 exposure.

10.4.2 Cardiovascular Effects

Very few reports on the cardiovascular effects of O_3 and other photochemical oxidants in animals have been published. Brinkman et al. (1964) studied structural changes in the cell membranes and nuclei of myocardial muscle fibers in adult mice exposed to O_3. After a 3-week exposure to 0.20 ppm of O_3 for 5 hr/day, structural changes were noted, but these effects were reversible about 1 month after exposure. However, because this study had severe design and methodology limitations, the results should be considered questionable until independently verified.

Bloch et al. (1971) studied the effects of O_3 on pulmonary arterial pressure in dogs. They exposed 31 dogs to 1.0 ppm of O_3 daily for various hours for 17 months. Ten percent (3 dogs) of the animals developed pulmonary arterial hypertension, and approximately 30 percent (9 dogs) had excessive systolic pressure, but there was no proportional relationship between pulmonary arterial hypertension and O_3 exposure. Unless sample sizes were too small to find adequate dose-response effects, the authors attributed the results to genetic susceptibility.

Revis et al. (1981) studied the effects of O_3 and cadmium, singly and combined, in rats. The rats were exposed to 0.60 ppm ozone of O_3 5 hr/day for 3 consecutive days or to 3 mg/m^3 cadmium for 1 hr or to both pollutants. All exposure treatments resulted in increases in systolic pressure and heart rate.

Neither diastolic pressure or mean pressure was affected. No additive or antagonistic effects were seen with the pollutant combinations.

Costa et al. (1983) measured heart rate and standard intervals of cardiac electrical activity from the electrocardiographic (EKG) tracings of rats exposed to 392, 1568, or 3920 μg/m^3 (0.2, 0.8, or 2 ppm) of O_3 6 hr/day, 5 days/week for 62 exposure days as part of a more extensive evaluation of lung function (Section 10.3.2). Heart rate was not altered by O_3 exposure. The predominant effects occurred at the highest O_3 concentration (3920 μg/m^3, 2 ppm) at which there was evidence of partial A-V blockade and distorted ventricular activity, often associated with repolarization abnormalities.

Friedman et al. (1983) evaluated the effects of a 4-hr exposure to 588 and 1960 μg/m^3 (0.3 and 1.0 ppm) of O_3 on the pulmonary gas-exchange region of dogs ventilated through an endotracheal tube. Pulmonary capillary blood flow and arterial O_2 pressure (PaO_2) were decreased 30 min following exposure to both O_3 concentrations, and arterial pH (pH_a) was decreased following exposure to 1960 μg/m^3 (1.0 ppm) of O_3. Decreases in pulmonary capillary blood flow persisted 24 hr following exposure to 588 and 1960 μg/m^3 (0.3 and 1.0 ppm) of O_3 and as long as 48 hr following exposure to 1960 μg/m^3 (1.0 ppm) of O_3. Persistent decreases in pH_a and PaO_2 were observed 24 hr following exposure to 1960 μg/m^3 (1.0 ppm) of O_3. Pulmonary edema, determined histologically and by increased lung water content and tissue volume, was observed 24 hr following exposure to 1960 μg/m^3 (1.0 ppm) of O_3. The data indicate that O_3 exposure can cause both acute and delayed changes in cardiopulmonary function.

10.4.3 Hematological and Serum Chemistry Effects

Hematological effects reported in laboratory animals and man after inhalation of near-ambient O_3 concentrations ($\leq$ 1960 μg/m^3; $\leq$ 1.0 ppm) indicate that O_3 or some reaction product of O_3 can cross the blood-gas barrier. In addition to reports of morphological and biochemical effects of O_3 on erythrocytes, chemical changes have also been detected in serum after *in vitro* and *in vivo* O_3 exposure. Hematological parameters are frequently used to evaluate O_3 toxicity, because red blood cells (RBCs) are structurally and metabolically simple and well understood, and because the relatively noninvasive methods involved in obtaining blood samples from animals and man make blood samples available for study.

10.4.3.1 Animal Studies - In Vivo Exposures. The effects of *in vivo* O_3 exposure in animals, including studies reviewed in the previous O_3 criteria document (U.S. Environmental Protection Agency, 1978), are summarized in Table 10-18.

Effects of O_3 on the blood were first reported by Christiansen and Giese (1954) after they detected an increased resistance to hemolysis of RBCs from mice exposed to 1960 $\mu g/m^3$ (1.0 ppm) for 30 min. Goldstein et al. (1968) reported a significant decrease in RBC acetylcholinesterase (AChE) activity after exposure of mice to 15,680 $\mu g/m^3$ (8 ppm) of O_3 for 4 hr. Menzel et al. (1975a) observed the presence of Heinz bodies in approximately 50 percent of RBCs in the blood of mice exposed to 1666 $\mu g/m^3$ (0.85 ppm) of O_3 for 4 hr. About 25 percent of RBCs contained Heinz bodies after continuous exposure of mice to 0.85 ppm of O_3 for 3 days. Heinz bodies are polymers of methemoglobin formed by oxidant stress; they appear to attach to the inner membrane of the RBC. However, Chow et al. (1975) detected no significant changes in GSHs, G-6-PDH, oxidized glutathione reductase, or GSH peroxidase in RBCs of rats or monkeys exposed to the same O_3 concentration 8 hr/day for 7 days.

In more recent studies, Clark et al. (1978) investigated the biochemical changes in RBCs of squirrel monkeys exposed to 1410 $\mu g/m^3$ (0.75 ppm) of O_3 4 hr/day for 4 days. They observed an increase in RBC fragility with decreases in GSH and AChE activities. No changes were detected in G-6-PDH or lactic dehydrogenase (LDH) activities. After a 4-day recovery period, RBC fragility was still significantly increased, although to a lesser degree. AChE activity returned to control levels at 4 days postexposure; however, RBC GSH remained significantly lowered.

Ross et al. (1979) investigated the effects of O_3 on the oxygen-delivery capacity of erythrocytes. After exposure of rabbits to 1960 or 7880 $\mu g/m^3$ (1 or 3 ppm) of O_3 for 4 hr, no changes were detected in RBC 2,3-diphosphoglycerate concentration, oxyhemoglobin dissociation curve, or heme-oxygen binding of RBCs. Analysis of blood parameters 24 hr after exposure revealed no delayed effects of O_3.

Alterations in RBC morphology have been previously observed in O_3-exposed laboratory animals and man (Brinkman et al., 1964; Larken et al., 1978). Similar observations have recently been made in monkeys exposed to 1254 $\mu g/m^3$ (0.64 ppm) of O_3 for 8 hr/day over a 1-yr period (Larkin et al., 1983). Ultrastructural SEM studies of RBC's following exposure to O_3 demonstrated

TABLE 10-18. HEMATOLOGY: ANIMAL -- IN VIVO EXPOSURE

Ozone concentration µg/m³	Ozone concentration ppm	Measurement[a] method	Exposure duration and protocol	Observed effect(s)[b]	Species	Reference
110	0.056	C	93 days	Decreased whole blood cholinesterase, which returned to normal 12 days after exposure ceased.	Rat	Eglite, 1968
118 235 470 941	0.6 0.12 0.24 0.48	UV	2.75 hr	RBC survival decreased at 0.06, 0.12, and 0.48 ppm; no concentration-response relationship.	Rabbit	Calabrese et al., 1983a
392	0.2	ND	4 hr	Increased osmotic fragility and spherocytosis of RBC's.	Rabbit	Brinkman et al., 1964
392	0.2	UV	8 hours/day, 5 days/week, 3 weeks	Increased serum glutamic pyruvic transaminase and hepatic ascorbic acid. No change in blood catalase.	Mouse	Veninga, 1970
392	0.2	UV	60 min	Small decrease in total blood serotinin.	Rabbit	Veninga, 1967
392-1960	0.2-1.0	UV	1-4 hr	Plasma creatine phosphokinase activity altered immediately and 15 min postexposure; no effect 30 min postexposure. No change in plasma histamine or plasma lactic acid dehydrogenase.	Mouse	Veninga et al., 1981
490 980 1372	0.25 0.50 0.70	UV	2.75 hr	RBC survival decreased at 0.25 ppm only.	Sheep	Moore et al., 1981a
627	0.32	UV	6 hr ± dietary vitamin E	Increased erythrocyte G-6-PD and decreased AChE (both diets). Increased plasma vitamin E (both diets).	Mouse	Moore et al., 1980
784	0.4	ND	6 hr/day, 5 days/week, 6 months	No change serum trypsin inhibitor capacity.	Rabbit	P'an and Jegier, 1971

TABLE 10-18. HEMATOLOGY: ANIMAL -- IN VIVO EXPOSURE (continued)

Ozone concentration $\mu g/m^3$	Ozone concentration ppm	Measurement[a] method	Exposure duration and protocol	Observed effect(s)[b]	Species	Reference
784	0.4	ND	6 hr/day, 5 days/week, 10 months	Increase in serum protein esterase.	Rabbit	Jegier, 1973
784	0.4	ND	10 months	Increase in serum protein esterase.	Rabbit	P'an and Jegier, 1972
784	0.4	ND	6 hr/day, 5 days/week, 10 months	Decreased serum albumin concentration. Increased concentration of α- and δ-globulins. Not much change in β-globulin. No change in total serum proteins.	Rabbit	P'an and Jegier, 1976
980	0.5	UV	2.75 hr	Decreased erythrocyte GSH.	Sheep	Moore et al., 1981b
980	0.5	MAST	Continuous, 23 days	Increased hemolysis of erythrocytes of animals depleted of vitamin E. No such change when rats received vitamin E supplements.	Rat	Menzel et al., 1972
980	0.5	NBKI	8 hr/day, 7 days	No change in GSH level or activities of GSH peroxidase, GSH reductase, or G-6-PD in erythrocytes.	Monkey, rat	Chow et al., 1975
1254	0.64	UV	8 hr/day, 1 yr	Altered RBC morphology: decreased number of discocytes, increased number of knizocytes, stomatocytes, and spherocytes. No effect on RBC FA composition.	Monkey	Larkin et al., 1983
1470	0.75	ND	4 hr/day, 4 days	RBC's: Increased fragility; decreased GSH, AChE; no effect on LDH, G-6-PD.	Monkey	Clark et al., 1978

TABLE 10-18. HEMATOLOGY: ANIMAL -- IN VIVO EXPOSURE (continued)

Ozone concentration μg/m³	 ppm	Measurement[a] method	Exposure duration and protocol	Observed effect(s)[b]	Species	Reference
1568	0.8	NBKI	7 days	Increased activity of GSH peroxidase, pyruvate kinase, and lactate dehydrogenase; and decrease in red cell level of GSH of vitamin E-deficient animals. Animals in both vitamin E-deficient and supplemented diet groups exhibited no change in activities of G-6-DP, catalase, and superoxide dismutase and in levels of thiobarbituric acid reactants, methemoglobin, hemoglobin, and reticulocytes.	Rat	Chow and Kaneko, 1979
1568	0.8	NBKI	8 hr/day, 7 days	No change in total lactate dehydrogenase activity or isoenzyme pattern in plasma or erythrocytes.	Monkey	Chow et al., 1977
1568	0.8	NBKI	Continuous, 29 days	Increased lysozyme activity by day 3.	Rat	Chow et al., 1974
1666	0.85	MAST	4 hr	Increased Heinz bodies in RBC's (decreased with continual exposure).	Mouse	Menzel et al., 1975a
1686	0.86	ND	8 hr/day, 5 days/week, 6 months	Increased infestation and mortality after infection with *Plasmodium berghei*. Increased acid resistance of erythrocytes.	Mouse	Schlipkoter and Bruch, 1973
1960	1.0	UV	4 hr ± vitamin E	Decreased filterability. No protection by vitamin E. No lipid peroxidation.	Mouse	Dorsey et al., 1983
1960	1.0	ND	30 min	Increased resistance to erythrocyte hemolysis.	Mouse	Mizoguchi et al., 1973; Christiansen and Giese, 1954

TABLE 10-18. HEMATOLOGY: ANIMAL -- IN VIVO EXPOSURE (continued)

Ozone concentration µg/m^3	Ozone concentration ppm	Measurement[a] method	Exposure duration and protocol	Observed effect(s)[b]	Species	Reference
1960- 3920	1.0 2	CHEM	2 or 7 days	No changes.	Rat, guinea pig	Cavender et al., 1977
1960 5880	1.0 3.0	CHEM	4 hr	No effects on oxyhemoglobin affinity, 2,3-DPG concentrations, heme-O_2 binding.	Rabbit	Ross et al., 1979
2940 11,760 15,680	1.5 6.0 8.0	UV	3 days 4 days 4 days	No effect on SOD, GPx, K^+ influx ratios (all levels). Increased Hb, Hct, echinocytes II & III (6 & 8 ppm); echinocytes correlated with petechia in lungs, indicative of vascular endothelial damage.	Rat	Larkin et al., 1978
7840	4.0	UV	2, 4, or 8 hr	Increased plasma concentrations of $PGF_2\alpha$ and PGE_2.	Rat	Giri et al., 1980
9800	5.0	CHEM	3 hr	Inhibition of serum monoamine oxidase.	Rat	Suzuki, 1976
19,600	10.0	I	1 hr/week, 6 weeks	Production of serum antibodies that reacted with ozonized egg albumin but not native ovalbumin.	Rabbit	Scheel et al., 1959

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[a] Measurement method: ND = not described; CHEM = gas phase chemiluminescence; UV - UV photometry; NBKI = neutral buffered potassium iodide; MAST = KI - coulometric (Mast meter); I = iodometric.

[b] Abbreviations used: RBC = red blood cell; G-6-PD = glucose-6-phosphate dehydrogenase; AChE = acetylcholinesterase; GSH = reduced glutathione; GSH peroxidase = glutathione peroxidase; GSH reductase = glutathione reductase; FA = fatty acid; LDH = lactic dehydrogenase; 2,3-DPG = 2,3-diphosphoglycerate; SOD = superoxide dismutase; GPx = glutathione peroxidase; K = potassium, Hb = hemoglobin; Hct = hematocrit; $PGF_2\alpha$ = prostaglandin $F_2\alpha$; PGE_2 = prostaglandin E_2.

[c] Spectrophotometric method using dihydroacridine

reduced numbers of normal discocytes and increased numbers of knizocytes, stomatocytes, and spherocytes, which were either absent or found in small numbers in the blood of air-exposed controls. Despite changes in shape, there were no differences in the fatty acid composition of the erythrocyte total lipids. Values for hematocrit, hemoglobin, mean corpuscular volume, and red cell and reticulocyte count were the same in control and O_3-exposed animals. Moore et al. (1981a) reported reduced RBC survival in sheep exposed to 490 μg/m^3 (0.25 ppm) of O_3 for 2.75 hr. Similar reductions in RBC survival were reported following 2.75-hr exposures to O_3 concentrations as low as 118 and 235 μg/m^3 (0.06 and 0.12 ppm) in rabbits (Calabrese et al., 1983a).

Vitamin E deficiency has been associated with an increased hemolysis in rats and other animal species (Scott, 1970; Gross and Melhorn, 1972). Chow and Kaneko (1979) reported significant increases in RBC GSH peroxidase, pyruvate kinase, and LDH activities, and a decrease in RBC GSH after exposure of vitamin E-deficient rats to 1568 ug/m^3 (0.8 ppm) of O_3 continuously for 7 days. These effects were not observed in vitamin E-supplemented rats (45 ppm of vitamin E for 4 months). The activities of G-6-PD, catalase, superoxide dismutase, and levels of TBA reactants, methemoglobin and reticulocytes were not altered by O_3 exposure or by vitamin E status.

Moore et al. (1980) investigated the effects of dietary vitamin E on blood of 9-month-old C57L/J mice exposed to 627 μg/m^3 (0.32 ppm) of O_3 for 6 hr. Animals were maintained on vitamin E-deficient, or supplemented (3.9 mg tocopherol/100 lb., twice the minimal daily requirement) diets for 6 weeks before O_3 exposure. Mice on the vitamin E-deficient diet showed a 24-percent increase in G-6-PD activity over controls after O_3 exposure, and mice fed a supplemented diet exhibited a 19-percent increase. Decreases in AChE activity were observed in both vitamin E-deficient (19-percent decrease) and vitamin E-supplemented (12-percent decrease) groups.

Dorsey et al. (1983) evaluated the effects of O_3 on RBC deformability after exposure of vitamin E-deficient and supplemented (105 mg of tocopherol per kg of chow) male CD-1 mice to 588 μg/m^3 (0.3 ppm), 1372 μg/m^3 (0.7 ppm), or 1960 μg/m^3 (1.0 ppm) of O_3 for 4 hr. After incubation of RBCs in buffer (0.9 percent RBCs) for up to 6 hr at 25°C, the time required for 2.0 ml of RBC suspension to pass through a 3-μm pore size filter was determined. Exposure of mice to 1960 μg/m^3 (1.0 ppm) or 1372 μg/m^3 (0.7 ppm) of O_3 and incubation of RBCs for 6 hr resulted in a significant increase in filtration time of RBCs from O_3-exposed mice, and a lack of protection by dietary vitamin E. The hematocrit of vitamin E-deficient mice exposed to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 was significantly greater than that of nonexposed vitamin E-supplemented mice. The increased hematocrit was attributed to a loss of RBC deformability, and sphering resulting in decreased packing of cells during centrifugation for hematocrit determination. No TBA reactants were detected in the blood of exposed animals, with or without vitamin E.

10.4.3.2 In Vitro Studies. The effects of *in vitro* O_3 exposure of animal blood have been studied by a number of investigators, and these reports are summarized in Table 10-19.

The effects of *in vitro* O_3 exposure on human RBCs have been evaluated by using a number of different end points, such as increases in complement-mediated cell damage (Goldstein, B., et al., 1974), formation of Heinz bodies (Menzel et al., 1975b), decreases in RBC native protein fluorescence (Goldstein and McDonaugh, 1975), and decreases in concanavalin A agglutinability (Hamburger et al., 1979). Exposure of RBCs or their membranes to O_3 has also been shown to inhibit (Na+ - K+) ATPase (Kindya and Chan, 1976; Chan et al., 1977; Koontz and Heath, 1979; Freeman et al., 1979; Freeman and Mudd, 1981). Kindya and Chan (1976) proposed that inhibition of ATPase by O_3 caused spherocytosis and increased fragility of RBCs after O_3 exposure. (See Table 10-20 for a summary of the human *in vitro* studies.)

Kesner et al. (1979) demonstrated that O_3-treated phospholipids inhibited RBC membrane ATPase. Addition of semicarbazide to O_3-exposed phospholipids before mixing with RBC membranes substantially reduced the inhibitory effect, suggesting that the inhibitors may be carbonyl compounds. In addition, a slower-forming semicarbazide-insensitive inhibitor was formed.

Verweij and Steveninck (1980, 1981) reported that semicarbazide and also p-aminobenzoic acid (PABA) might protect by acting as O_3 scavengers. Spectrin (a major glycoprotein component of the RBC membrane) solution was treated by bubbling O_3-containing O_2 through the solution at 4 ml/min (2.5 μM/min of O_3) for 1 or 2 min. Semicarbazide (40 μM) or PABA (40 μM) inhibited the cross-linking of O_3-exposed spectrin. The inhibition of AChE and hexokinase activities of RBC ghosts exposed to O_3 was also partially prevented by these two agents, as was K^+ influx into whole RBCs. The authors attributed the inhibition of ATPase to oxidation of phospholipids with subsequent cross-linking of membrane protein by lipid peroxidation products. Because the reaction of ozonolysis

TABLE 10-19. HEMATOLOGY: ANIMAL -- IN VITRO EXPOSURE

Ozone concentration		Measurement[a] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
980- 3920	0.5 2.0	CHEM	2 hr	Decrease in agglutination of erythrocytes by concanavalin A.	Rat	Hamburger and Goldstein, 1979
1960- 13,132	1.0 6.7	NBKI	90 min- 4 hr	Decreased erythrocyte catalase levels at $\geq$ 5 ppm when animals were pretreated with aminotriazole.	Rat, mouse	Goldstein, 1973
2156 4508	1.1 2.3	UV	16 hr	No effect on hemoglobin. No change in organic free radicals as measured by EPR spectra. No statistics.	Mouse	Case et al., 1979

[a] Measurement method: CHEM = gas phase chemiluminescence; UV = UV photometry; NBKI = neutral buffered potassium iodide.

TABLE 10-20. HEMATOLOGY: HUMAN - *IN VITRO* EXPOSURE

Ozone[a] concentration	Measurement[b] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
980 μg/m^3 (0.5 ppm) 1960 μg/m^3 (1.0 ppm)	CHEM	0.5-2 hr	Decreased agglutination of RBCs by concanavalin A.	Human	Hamburger et al., 1979
O_3-treated phospholipids	ND	5, 10, 15, and 20 min	Decreased ATPase activity.	Human (RBC ghosts)	Kesner et al., 1979
4 μM/min	I	1 min	Decreased ATPase activity.	Human (RBC ghosts)	Kindya and Chan, 1976
Methylozonide 10^{-4}-2×10^{-3} M	ND	30 min	Heinz body formation. Prevented by dietary vitamin E.	Human	Menzel et al., 1975b
750 nM/min	NBKI	14.3 or 43.0 nMol of O_3 per 10^6 cell equivalent	RBC -- No effect on ATPase. Decreased cation transport. RBC ghosts -- decreased ATPase activity.	Human	Koontz and Heath, 1979
106 nM/min	NBKI	5, 10, 20, 30, 40 and 50 min	Decreased activity of purified α_1-proteinase inhibitor.	Human	Johnson, 1980
300 nM/min	NBKI	ND	Decreased glyceraldehyde-3-PD. Decreased ATPase. No statistics.	Human (RBC ghosts)	Freeman et al., 1979
0-9.8 μM/g of Hb 0.84 μM/min	NBKI	0-2 hr	Decreased GSH. No effect on Hb or on glucose uptake.	Human (RBCs, RBC ghosts)	Freeman and Mudd, 1981
78400 μg/m^3 (40 ppm)	NBKI	2 hr	Increased complement-mediated cell damage.	Human	Goldstein, B., et al., 1974
1,960 μg/m^3 (1.0 ppm)	NBKI	20 and 60 min	Decreased native protein fluorescence. No statistics.	Human (RBC ghosts)	Goldstein et al., 1975

TABLE 10-20. HEMATOLOGY: HUMAN - IN VITRO EXPOSURE (continued)

Ozone[a] concentration	Measurement[b] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
40 nM/min	I	4 min	Decreased ATPase activity; lost 40% membrane sulfhydryls. Lipid peroxidation and protein crosslinking detected. Pretreatment with semicarbazide prevented crosslinking.	Human (RBC ghosts)	Chan et al., 1977
2.5 μM/min	I	20, 40, and 60 min	Cross-linking of membrane proteins inactivation of glyceraldehyde-3-phosphate dehydrogenase.	Human	Verweij and Steveninck, 1980
2.5 μM/min	I	20, 40, and 60 min	Crosslinking of spectrin. Decreased ACHase activity. Increased K+ leakage from RBCs. Semicarbazide and p-amino benzoic acid prevented these O_3 effects.	Human (RBC ghosts)	Verweij and Steveninck, 1981

[a] Not ranked by concentration; listed by reported values.
[b] Measurement method: ND = not described; CHEM = gas phase chemiluminescence; NBKI = neutral buffered potassium iodide; I = iodometric.

products with semicarbazide and PABA during O_3 treatment of RBCs was not directly measured in these studies, the protective mechanism remains unclear.

In a recent study, Freeman and Mudd (1981) investigated the in vitro reaction of O_3 with sulfhydryl groups of human RBC membrane, proteins, and cytoplasmic contents. After exposure of RBCs to O_3 in O_2 at 20 ml/min (0.84 μMol/min of O_3) for up to 2 hr, oxidation of intracellular GSH was observed. Ozone exposure produced membrane disulfide cross-links in RBC ghosts but not in intact RBCs. Neither oxyhemoglobin content nor glucose uptake was affected by O_3 exposure of RBCs. These data support earlier studies of Menzel et al. (1972) that reported decreased RBC GSH levels following exposure of rats to 980 $\mu g/m^3$ (0.5 ppm) of O_3 continuously for 23 days.

Although in vitro studies using animal and human RBCs have provided information on the possible mechanism by which O_3 may react with cell membranes and RBCs, extrapolation of these data to in vivo O_3 toxicity in man is difficult. In most in vitro studies, RBCs were exposed by bubbling high O_3 concentrations (> 1 ppm) through cell suspensions. Not only were the O_3 concentrations unrealistic and the method of exposure nonphysiological, but the toxic species causing RBC injury may be different during in vitro and in vivo O_3 exposures. Because of its reactivity, it is uncertain that O_3 per se reaches the RBCs after inhalation but may instead appear in blood in the form of less reactive products (e.g., lipid, peroxides). However, during in vitro exposure of RBC suspensions, O_3 or highly reactive free-radical products (e.g., hydroxyl radical, superoxide anion, singlet oxygen) may be the cause of injury.

10.4.3.3 Changes in Serum. In addition to O_3's effects on RBCs, changes have been detected in the serum of animals exposed to O_3. P'an and Jegier (1971) investigated the effects of 784 $\mu g/m^3$ (0.4 ppm) of O_3 6 hr/day, 5 days/week for 6 months on the serum trypsin inhibitor capacity (TIC) of rabbits. With the exception of a sharp rise after the first day of exposure, TIC values remained within normal limits. However, after exposure for 10 months, the TIC had progressively increased to about three times the normal level (P'an and Jegier, 1972). Microscopic evaluation suggested that the rise in TIC may have been due to the thickening of small pulmonary arteries. The results from this study are questionable, however, because the rabbits may have had intercurrent infectious disease, which was more severe in the exposed animals (Section 10.3.1).

P'an and Jegier (1976) also reported changes in serum proteins after exposure of rabbits to 784 μg/m^3 (0.4 ppm) and 1960 μg/m^3 (1.0 ppm) of O_3. Following exposure to 784 μg/m^3 (0.4 ppm) of O_3 for 105 days, the albumin concentrations began to decrease, and α- and δ-globulin concentrations began to increase. At the end of 210 days of exposure, the mean albumin level fell 16 percent, the α-globulin level rose 78 percent, and the δ-globulin levels fell 46 percent. No significant changes were observed in total protein concentration.

Chow et al. (1974) observed that the serum lysozyme activity of rats increased significantly during continuous (24 hr/day) but not during intermittent (8 hr/day) exposure to 1568 μg/m^3 (0.8 ppm) of O_3 for 7 days. The increased release of lysozyme into the plasma was suggested to be a result of O_3 damage to alveolar macrophages.

After exposure of rats to 7840 μg/m^3 (4 ppm) of O_3 for 2, 4, and 8 hr, Giri et al. (1980) observed increases in plasma prostaglandin (PG) $F_{2\alpha}$ of 186, 109, and 25 percent, respectively. Plasma concentrations of PGE_2 were approximately twice the control levels after exposure for 2 or 8 hr, but only a slight increase was observed after exposure for 4 hr.

Veninga et al. (1981) reported that short-term exposures of mice to low O_3 concentrations induced changes in serum creatine phosphokinase (CPK) activity. Ozone doses were expressed as the product of concentration and time; the maximum O_3 concentration was 1600 μg/m^3 (0.8 ppm), and the maximum exposure time was 4 hr. Alterations in CPK were detected immediately and 15 min after termination of the exposure. By 30 min postexposure, the CPK activities had returned to control levels. Neither plasma histamine nor plasma LDH was altered by the range of O_3 doses employed. The authors concluded that these responses may represent adaptation of the animals to O_3 toxicity by enhanced metabolic processes.

10.4.3.4 Interspecies Variations. The use of animal models to investigate the effects of O_3 on the blood is complicated, because few species respond like humans. The rodent model has been most commonly used to predict the effects of O_3 on human RBCs. The reliability of this model was recently challenged by Calabrese and Moore (1980) on the following grounds: (1) ascorbic acid synthesis was significantly increased in mice following O_3 exposure (Veninga and Lemstra, 1975), (2) ascorbic acid protected human G-6-PD-deficient RBCs *in vitro* from the oxidant stress of acetylphenylhydrazine (Winterbourn, 1979), and (3) humans lack the ability to synthesize ascorbic acid. Although Calabrese and Moore (1980) stressed that this hypothesis is based on a very limited data base, they point out the importance of developing animal models that can accurately predict the response of human G-6-PD-deficient humans to oxidant stressor agents. In another report, Moore et al. (1980) suggested that C57L/J mice may present an acceptable animal model, because these mice responded to O_3 exposure (627 $\mu g/m^3$, 0.32 ppm for 6 hr) in a manner similar to that of humans, with increases in serum vitamin E and G-6-PD activity. Unlike many other mouse strains, the C57L/J strain has low G-6-PD activity, which is similar to that found in human RBCs. Moore et al. (1981b) also followed up on the proposed use of Dorset sheep as an animal model for RBC G-6-PD deficiency in humans (National Academy of Sciences, 1977). However, Dorset sheep were found to be no more sensitive than normal humans with respect to O_3-induced changes in GSH and also differed from humans in the formation of methemoglobin. Further studies (Calabrese et al., 1982, 1983b; Williams et al., 1983a,b,c) demonstrated that the responses of sheep and normal human erythrocytes were very similar when separately incubated with potentially toxic O_3 intermediates, but G-6-PD-deficient human erythrocytes were considerably more susceptible. Consequently, the authors also questioned the value of the sheep erythrocyte as a quantitatively accurate predictive model.

10.4.4 Reproductive and Teratogenic Effects

Pregnant animals and developing fetuses may be at greater risk to effects from photochemical oxidants, because the volume of air inspired by females generally increases from 15 to 50 percent during pregnancy (Allman and Dittmer, 1971). Before 1978, experiments designed to investigate the reproductive effects of photochemical oxidants often used complex mixtures of gases, such as irradiated auto exhaust (see Section 10.5), or they used oxidant concentrations greater than those typically found in ambient air. Brinkman et al. (1964) exposed pregnant mice to lower concentrations of O_3, but the results of their experiments are difficult to interpret, because the time of O_3 exposure during gestation and postparturition was not specified. They reported that mice exposed to 196 or 392 $\mu g/m^3$ (0.1 or 0.2 ppm) of O_3 for 7 hr/day and 5 days/week over 3 weeks had normal litter sizes, compared with air-exposed controls. However, there was greater neonatal mortality in the litters of O_3-exposed mice, even at the exposure level of 196 $\mu g/m^3$ (0.1 ppm) of O_3 (Table 10-21). Unfortunately, without more details on the period of exposure,

TABLE 10-21. REPRODUCTIVE AND TERATOGENIC EFFECTS OF OZONE

Ozone concentration		Measurement[a] method	Exposure duration and protocol	Observed effect(s)	Species	Reference
μg/m³	ppm					
196	0.1	ND	7 hr/day, 5 days/week for 3 weeks	Increased neonatal mortality (4.9 to 6.8% vs. 1.6 to 1.9% for controls)[b].	Mouse	Brinkman et al., 1964
392	0.2	ND	7 hr/day, 5 days/week for 3 weeks	Unlimited growth of incisors (5.4% incidence vs. 0.9% in controls)[b].	Mouse	Veninga, 1967
862	0.44	I	8 hr/day over entire period of organogenesis (days 6 to 15)	Decreased average maternal weight gain.	Rat	Kavlock et al., 1979
2920	1.49		Continuous during mid-gestation	Increased fetal resorption rate (50% vs. 9% for controls).		
1960	1.0	I	Continuous during late gestation	Slower development of righting, eye opening, and horizontal movement; delayed grooming and rearing behavior.	Rat	Kavlock et al., 1980
1960	1.0		Continuous during mid- (day 9 to 12) or late (days 17 to 20) gestation	Average weight reduced 6 days after birth.		
2940	1.5		Continuous during late gestation (days 17 to 20)	3 males (14.3%) were permanently runted.		

[a] Measurement method: ND = not described, I = iodometric (Saltzman and Gilbert, 1959).

[b] No statistical evaluation.

it is impossible to ascertain whether the decreased infant survival rate was due to development interference in utero, to a direct effect on the pups, or to a nutritional deficiency caused by parental anorexia or reduced lactation, or a combination of these effects. When using a similar experimental protocol, Veninga (1967) found that mice exposed to 392 $\mu g/m^3$ (0.2 ppm) of O_3 for 7 hr/day, 5 days/week during embryological development and the 3 weeks after birth (total exposure time not reported) had an increased incidence of excessive tooth growth, although no statistical evaluation was provided.

In more recent experiments, Kavlock et al. (1979) exposed pregnant rats to O_3 for precise periods during organogenesis. No significant teratogenic effects were found in rats exposed 8 hr/day to concentrations of O_3 varying from 863 to 3861 $\mu g/m^3$ (0.44 to 1.97 ppm) during early (days 6 to 9), mid (days 9 to 12), of late (days 17 to 20) gestation, or the entire period of organogenesis (Days 6 to 15). Continuous exposure of pregnant rats to 2920 $\mu g/m^3$ (1.49 ppm) of O_3 in midgestation resulted in increased resorption of embryos. A single dose of 150 mg/kg sodium salicylate followed by 1960 $\mu g/m^3$ (1.0 ppm) of O_3 during midterm produced a significant synergistic increase in the resorption rate, a decrease in maternal weight change, and an average fetal weight. Exposure of pregnant rats 8 hr/day to 862 $\mu g/m^3$ (0.44 ppm) of O_3 throughout the period of organogenesis also resulted in a significant decrease in average maternal weight gain.

In a follow-up study, Kavlock et al. (1980) investigated whether in utero exposure to O_3 can affect postnatal growth or behavioral development. In contrast to the results of Brinkman et al. (1964), neonatal mortality of rats was not increased by exposure to 2940 $\mu g/m^3$ (1.5 ppm) of O_3 for periods of 4 days during gestation. Pups from litters of females exposed to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 during mid- (days 9 to 12) or late (days 17 to 20) gestation exhibited significant dose-related reductions in weight 6 days after birth. Pups from the late gestation exposure group were affected to a greater extent and for a longer period of time after parturition. In fact, several males exposed to 2940 $\mu g/m^3$ (1.5 ppm) of O_3 (1.0 ppm) of O_3 during late gestation were also significantly slower in the development of early movement reflexes and in the onset of grooming and rearing behaviors. The authors pointed out that it is impossible to distinguish between prenatal and postnatal contributions to the behavioral effects, because foster parent procedures were not used to raise the pups.

10.4.5 Chromosomal and Mutational Effects

10.4.5.1 Chromosomal Effects of Ozone. A large portion of the data available on the chromosomal and mutational effects of O_3 was derived from investigations conducted above 1,960 $\mu g/m^3$ (1 ppm) of O_3, and their relevance to human health is questionable. However, for completeness of the review of the literature, and for possible insight into the mechanisms by which O_3 may produce genotoxicity, this discussion will not be limited to data derived from research conducted at or below 1,960 $\mu g/m^3$ (1 ppm) of O_3. Data derived predominantly from in vitro experiments conducted at O_3 concentrations in excess of 1,960 $\mu g/m^3$ (1 ppm) of O_3 will be discussed first (Table 10-22), followed by a discussion of the genotoxicity data from both in vitro and in vivo research conducted at or below 1 ppm of O_3 (Table 10-23).

The potential for genotoxic effects relating to O_3 exposure was predicted from the radiomimetic properties of O_3. The decomposition of O_3 in water produces OH and HO_2 radicals, the same species that are generally considered to be the biologically active products of ionizing radiation. Fetner (1962) reported that chromatid deletions were induced in a time-dependent manner in human KB cells exposed to 15,680 $\mu g/m^3$ (8 ppm) of O_3 for 5 to 25 min. The chromatid breaks were apparently identical to those produced by x-rays. A 10-min exposure to 8 ppm of O_3 slightly more efficient in the production of chromatid breaks than 50 rad of x-rays. Significant mitotic delay was measured in neuroblasts from the grasshopper Chortophaga viridifaciata exposed to 3500 to 4500 $\mu g/L$ of O_3 in a closed system (Fetner, 1963).

Scott and Lesher (1963) measured a sharp loss of viability with Escherichia coli as the O_3 concentration was increased. Viability was reduced to zero when cells were exposed to 1 $\mu g/ml$ of O_3. Damage to cell membranes was evident by the leakage of nucleic acids and other cellular components from cells exposed to 0.18 $\mu g/ml$ of O_3.

The molecular mechanism for the clastogenic and lethal effects resulting from O_3 exposure are not precisely known. Bubbling 8 percent O_3 through a phosphate buffer solution (0.05M, pH 7.2) containing DNA caused an immediate loss in absorption at 260 nm and an increase in the absorption of the solution at wavelengths shorter than 240 nm (Christensen and Giese, 1954). A similar rate of degradation was observed with RNA and the individual purine and pyrimidine bases, nucleosides, and nucleotides. In a more recent report, Shiniki et al. (1981) examined the degradation of a mixture of 5' nucleotides, yeast

TABLE 10-22. CHROMOSOMAL EFFECTS FROM *IN VITRO* EXPOSURE TO HIGH OZONE CONCENTRATIONS

O_3 concentration[a]	Measurement[b] method	Exposure duration and protocol[c]	Observed effect(s)	Species	Reference
15,680 μg/m³ (8ppm)	UKI	5-25 min	Chromatid deletions.	Humans KB cells	Fetner, 1962
98,000 μg/m³ (50 ppm)	MAST[d]	30 min	*lex* mutants deficient in repair of x-ray-induced DNA strand breaks were more sensitive to lethal effects of O_3 than were the wild-type repair-proficient parental strains	*Escherichia coli*	Hamelin and Chung, 1974
98,000 μg/m³ (50 ppm)	MAST[d]	30 min	DNA Polymerase I mutant strains (KMBL 1787, 1789, 1791) were more sensitive to the cytotoxic effects of O_3, and DNA was degraded to a greater extent in the first 3 hr after O_3 exposure than strain KMBL 1788, which contains a normal DNA Polymerase I.	*E. coli*	Hamelin et al., 1977a
98,000 μg/m³ (50 ppm)	MAST[d]	30 min	Mucoid mutant strains (MQ 100 & 105) obtained by treating MQ 259 with O_3 yet having full complement of DNA repair enzymes were shown to be more sensitive to O_3 and degraded DNA to a greater extent than the *lon* + (MQ259) strain.	*E. coli*	Hamelin et al., 1977b
98,000 μg/m³ (50 ppm)	MAST[d]	up to 3 hrs	15 different DNA repair-deficient strains were tested for sensitivity to the cytotoxic effects of O_3; DNA Polymerase I was involved in DNA repair but Polymerases I and II and DNA synthetic genes dna A, B, and C were not; recombinational repair pathways, assayed with rec A and rec B strains, were only partially involved in the repair of O_3-induced DNA damage.	*E. coli*	Hamelin and Chung, 1978

TABLE 10-22. CHROMOSOMAL EFFECTS FROM *IN VITRO* EXPOSURE TO HIGH OZONE CONCENTRATIONS (continued)

O_3 concentration[a]	Measurement[b] method	Exposure duration and protocol[c]	Observed effect(s)	Species	Reference
0.1 μg/ml [51 ppm]	UV	60 min (70 ml/min)	Preferential degradation of yeast RNA at the N-glycosyl linkage; sugar-phosphate linkage was O_3 stable.	Yeast	Shiniki et al., 1981
0.5 μg/ml [255 ppm]	UV	30 min (330 ml/min)	5-ribonucleotide guanosine monophosphate was degraded most rapidly.		
0.18 μg/ml [92 ppm] 1.0 μg/ml [510 ppm]	UKI	ND	Release of nucleic acids; cell lethality.	*E. coli*	Scott and Lesher, 1963
0.5-6 μg/ml [255-3061 ppm]	NBKI	0-5 min	O_3 reacts with pyrimidine bases from nucleic acids (thymidine > cytosine > uracil).	*E. coli*	Prat et al., 1968
1-10 μg/ml [510-5100 ppm]	NBKI	30 min	Cell death and nonspecific chromosomal aberrations: shrunken and fragmented nuclei, clumped metaphase chromosomes and chromosome bridges.	Chick embryo fibroblasts	Sachsenmaier et al., 1965
5% [50,000 ppm]	NBKI	0-40 min	Rapid loss of glycolytic and respiratory capacity; loss of tumorigenicity after 20 min. exposure.	Mouse ascites cells	
3.5-4.5 μg/ml [1786-2296 ppm]	UKI	ND	Mitotic delay.	*Chortophaga viridifaciata*	Fetner, 1963
2% [20,000 ppm]	e	3 min	Abnormal nuclei; fragmentation.	Am. oyster	MacLean et al., 1973
8% [80,000 ppm]	GPT	5, 15, 60 s	Rapid degradation of nucleic acid bases, nucleosides or nucleotides in 0.05M phosphate buffer, pH 7.2.	ND	Christensen and Giese, 1954

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[a] Not ranked by air concentration; listed by reported exposure values and [approximate ppm conversions].

[b] Measurement method: MAST = KI-coulometric (Mast meter); NBKI = neutral buffered potassium iodide; UV = UV photometry; GPT = gas phase titration; UKI = unbuffered potassium iodide.

[c] O_3 flow rate given in (ml/min), when available. ND = not described.

[d] Concentrations of O_3 were not measured in the cell suspensions.

[e] O_3 analyzer (Fisher and Porter, Warminster, PA).

TABLE 10-23. CHROMOSOMAL EFFECTS FROM OZONE CONCENTRATIONS AT OR BELOW 1960 μg/m³ (1 ppm)

O_3 Concentration μg/m³	ppm	Measurement[a,b] method	Exposure[c] duration and protocol	Observed effect(s)[d]	Species	Reference
294 412 1940 451	0.15 0.21 0.99 0.23	NBKI NBKI	5 hr 5 hr 2 hr 5 hr (*in vitro*)	No effect induced by O_3 treatment on the frequency of chromosome or chromatid aberrations in Chinese hamster or mouse peripheral blood lymphocytes stimulated with PHA; no effect on spermatocytes in mice 8 wk following exposure.	Mouse Hamster	Gooch et al., 1976
2548-14,700	1.3-7.5	NBKI	ND (*in vitro*)	Peripheral blood lymphocytes exposed to O_3 in culture 12 hr after stimulation with PHA showed no increase in chromosome or chromatid aberrations.	Human lymphocytes	
3234-27,832	1.65-14.2	NBKI	ND (*in vitro*)	Peripheral blood lymphocytes exposed to O_3 in culture, 36 hr after PHA stimulation, showed no change in the frequency of chromosome or chromatid aberrations at any concentration except 7.23 ppm of O_3.	Human lymphocytes	
3920	2.0	NBKI	5-90 min (*in vitro*)	No apparent increase in the frequency of chromosome or chromatid aberrations 12 or 36 hr after PHA stimulation.	Human lymphocytes	
392	0.2	MAST UKI	5 hr (*in vivo*)	Combined exposure to O_3 and radiation (227-233 rad) produced an additive effect on the number of chromosome breaks measured in peripheral blood lymphocytes.	Hamster	Zelac et al., 1971b
470-588	0.24-0.3	MAST UKI	5 hr (*in vivo*)	A significant increase in chromosome aberrations (deletions, ring dicentrics) in the peripheral blood lymphocytes; increased break frequency was still apparent at 6 and 16 days following exposure.	Hamster	Zelac et al., 1971a

TABLE 10-23. CHROMOSOMAL EFFECTS FROM OZONE CONCENTRATIONS AT OR BELOW 1960 μg/m³ (1 ppm) (continued)

O_3 Concentration μg/m³	ppm	Measurement[a,b] method	Exposure duration and protocol[c]	Observed effect(s)[d]	Species	Reference
490-1960	0.25-1.0	UV	1 hr (*in vitro*)	Dose-related increase in SCE frequency in WI-38 diploid fibroblasts exposed in culture.	Human fibroblasts	Guerrero et al., 1979
588-1568	0.3-0.8	UV	8 days, continuous (*in vitro*)	Growth of cells from lung, breast, and uterine tumors were inhibited to a greater degree than IMR-90, a nontumor diploid fibroblast.	Human tumor cells	Sweet et al., 1980
843	0.43	UV, NBKI	5 hr (*in vivo*)	Increase in chromatid-type aberrations in peripheral blood lymphocytes of O_3-exposed hamsters; Increase in deletions at 7 days and increase in achromatic lesions at 14 days after exposure; chromosome-type lesions were not significantly different; no chromosomal aberrations in bone marrow lymphocytes; no change in SCE frequency in peripheral blood lymphocytes.	Hamster	Tice et al., 1978
3920	2.0		6 hr (*in vivo*)	No change in SCE frequency in peripheral blood lymphocytes.	Mouse	
1960-9800	1.0-5.0	CHEM NBKI	24 hr (*in vivo*)	Variable decrease in the molecular weight of DNA from peritoneal exudate cells of O_3 exposed mice becoming significant at 5 ppm; significant induction of single-strand breaks at 5 ppm.	Mouse	Chaney, 1981

[a] Measurement method: MAST = KI-coulometric (Mast meter); NBKI = neutral buffered potassium iodide; UV = UV photometry

[b] Calibration method: UKI = unbuffered potassium iodide; NBKI = neutral buffered potassium iodide.

[c] ND = not described.

[d] Abbreviations used: PHA = phytohemagglutinin; SCE = sister chromatid exchange.

t-RNA or tobacco mosaic virus RNA with O_3 (0.1 to 0.5 mg/L). The guanine moiety was found to be the most O_3-labile among the four nucleotides, whether the guanine was present as free guanosine monophosphate or incorporated into RNA. The sensitivity to degradation by O_3 among the four nucleotides was found to be, in decreasing order, GMP > UMP > CMP > AMP (GMP = guanosine monophosphate, U = uridine, C = cytidine, A = adenosine). Even after extensive ozonolysis of yeast t-RNA (0.5 µg/ml, 30 min) and substantial degradation of the guanine moieties, the RNA migrated as a single band on polyacrylamide gels. The band exhibited the same mobility as the intact t-RNA, indicating that although the glycosidic bond between the sugar and the base is O_3-labile, the sugar-phosphate backbone was intact and extremely stable against O_3. Prat et al. (1968) investigated the reactivity of the pyrimidines in E. coli DNA with O_3 (0.5 to 6 mg/L, 0 to 5 min) and radiation. Ozone preferentially reacted with thymidine, then with cytosine and uracil, in decreasing order of reactivity. The results are slightly different from those reported by Shiniki et al. (1981) in that the reactivity with uracil and cytidine are in reversed order.

There is evidence that single-strand breaks in DNA may contribute to the genotoxic effects of O_3. Radiosensitive lex mutants of E. coli, which were known to be defective in the repair of x-ray-induced single-strand breaks in DNA, were found to be significantly more sensitive to the cytotoxic effects of O_3 than the repair-proficient parental strain (Hamelin and Chung, 1974).

In an effort to investigate the nature of the O_3-induced lesion in DNA, Hamelin and coworkers investigated the survival of bacterial strains with known defects in DNA repair. Closely related strains of E. coli K-12 with mutations in DNA polymerase I were shown to be more sensitive to the cytotoxic effects of O_3 than the DNA polymerase proficient (pol +) strain (Hamelin et al., 1977a). Polymerase I-deficient strains also exhibited an extensive degradation of DNA in response to O_3 or x-ray treatment. The authors concluded that DNA polymerase I plays a key role in the repair of lesions produced in E. coli DNA by O_3 and that the unrepaired damage was responsible for the enhanced degradation of DNA and the enhanced cell killing observed in the pol- mutants. This interpretation of the data may not be entirely correct, because an enhanced degradation of DNA and an increased sensitivity to cell killing were also observed in a lon mutant strain of E. coli K-12 (Hamelin et al., 1977b). The lon mutant appears to have a full complement of DNA repair enzymes. With these mutants, there may be an enhanced DNA repair activity (evidenced by the extensive degradation of DNA), and the enhanced activity of the lon gene products was thought to be responsible for the increased cell killing observed with these strains when they were exposed to O_3.

Although DNA polymerase I was shown to be involved in the repair of O_3-induced DNA damage (Hamelin et al., 1977a), *E. coli* cell strains with mutations in DNA polymerase II or III were not found to be more sensitive to O_3 than the wild-type, suggesting that these enzymes are not involved in the repair of DNA damaged by O_3 (Hamelin and Chung, 1978). Mutant strains of *E. coli* with defects in DNA synthesis (DNA A, B, C, D, and G) showed no enhanced sensitivity to O_3. Therefore, the DNA gene products are probably not involved in the repair of O_3 damage. Recombinational repair mutants, rec A and rec B, only showed a slightly increased sensitivity to O_3 than the wild-type, suggesting that the rec gene products are only partially involved in the repair of O_3-induced DNA lesions (Hamelin and Chung, 1978).

Other effects have been observed than those described above on bacteria. In the commercial American oyster exposed to O_3-treated sea water (MacLean et al., 1973), fertilization occurred less readily and abnormal nuclei (degeneration, fragmentation) were observed approximately twice as frequently. Sachsenmaier et al. (1965) observed a rapid loss of glycolytic and respiratory capacity and subsequent loss of tumorigenicity in mouse ascites cells treated with O_3. These authors also reported that chicken embryo fibroblasts exposed to O_3 (1 to 10 μl/ml) for 30 min exhibited nonspecific alterations in cells resembling those seen after x-ray damage, including shrunken nuclei, clumped metaphase chromosomes, arrested mitosis, chromosome bridges and fragmented nuclei.

In the studies described up to this point, the investigators have predominantly examined the *in vitro* effects of extremely high O_3 concentrations on biological systems or biologically important cellular components. Although these investigations may be important for the elucidation of the types of damage or responses that might be expected to occur at lower O_3 concentrations, the most relevant data on the genotoxicity of O_3 should be obtained from investigations where the O_3 concentration did not exceed 1960 μg/m^3 (1 ppm). Research conducted at or below 1 ppm of O_3 will be presented below (See Table 10-24).

Several investigators have examined the *in vivo* cytogenetic effects of O_3 in rodents and human subjects. Until the reports of Zelac et al. (1971a,b),

TABLE 10-24. MUTATIONAL EFFECTS OF OZONE

O_3 concentration µg/m^3	ppm	Measurement[a] method	Exposure duration and protocol[b]	Observed effect(s)	Species	Reference
196	0.1	MAST	60 min (2.1 ml/min)	Various mutated, growth factor autotrophic states, were recovered; mutant strains differed from parental strains in sensitivity to UV light and excessive production of capsular polysaccharide.	*Escherichia coli* *(MQ 259)*	Hamelin and Chung, 1975a
58,800	30	NBKI	3 hr	Induction of a dominant lethal mutation during stages of spermatogenesis; sperm were found to be twice as sensitive as earlier stages.	*Drosophila virilis*	Erdman and Hernandez, 1982
98,000	50	UV	30 min (2.1 ml/min)	Radiation-sensitive mutant strains defective in repair of single strand (rad 51) and double strand (rad 52) DNA breaks were more sensitive to O_3 cell killing than either the wild-type or the UV light repair deficient strain (rad 3); recombinational repair-deficient strain (rad 6) was moderately sensitive to O_3.	*Saccharomyces cerevisae*	Dubeau and Chung, 1979
98,000	50	UV	30 min	Induction of forward mutations at 2 loci of adenine biosynthesis (strain C16-11C); induction of reversion mutation at 6 genetic loci (strain XV 185-14C); induction of intragenic and intergenic recombinational mutants (strain D7); O_3 was 20-200x less mutagenic than equitoxic exposures to UV light, x-rays, or MNNG.	*Saccharomyces cerevisae*	Dubeau and Chung, 1982

[a] Measurement method: MAST = KI-coulometric (Mast meter); NBKI = neutral buffered potassium iodide; UV = UV photometry

[b] O_3 flow rates given in (ml/min), where available.

the toxic effects of O_3 were generally assumed to be confined to the tissues directly in contact with the gas, such as the respiratory epithelium. Due to the highly reactive nature of O_3, little systemic absorption was predicted. Zelac, however, reported a significant increase in chromosome aberrations in peripheral blood lymphocytes from Chinese hamsters exposed to 392 µg/m^3 (0.2 ppm) for 5 hr. Chromosome breaks, defined as the sum of the number of deletions, rings and dicentrics, were scored in lymphocytes collected immediately after O_3 exposure and at 6 and 15 days postexposure. At all sampling times, there was an increase in the break frequency (breaks/ cell) in the O_3-exposed animals when compared with nonexposed control animals. Zelac et al. (1971b) reported that O_3 was additive with radiation in the production of chromosome breaks. Both O_3 and radiation produced chromosome breaks independently of each other. Simultaneous exposure to 0.2 ppm of O_3 for 5 hr and 230 rad of radiation resulted in the production of 40 percent more breaks than were expected from either agent alone and 70 percent of the total number of breaks expected from the combined effects of the two agents, if it was assumed that the effects were additive.

Chaney (1981) investigated the effects of O_3 exposure on mouse peritoneal exudate cells (peritoneal macrophages) stimulated by an i.p. injection of glycogen. Mice were subsequently exposed by inhalation to 1960 or 9800 µg/m^3 (1 or 5 ppm) of O_3 for 24 hr. A significant reduction in the average molecular weight of the DNA was observed in the peritoneal exudate cells from mice exposed to 9800 µg/m^3 (5 ppm) of O_3 but not in animals exposed to 1960 µg/m^3 (1 ppm) of O_3 for 24 hr. The reduction in the average molecular weight of DNA in O_3-exposed animals indicated the induction of single-strand breaks in the DNA. It should be noted, however, that the alkaline sucrose gradient method of determining the average molecular weight of the DNA does not discriminate between the frank strand-breaks in DNA, produced as a direct effect of the O_3 treatment, and the induction of alkaline-labile lesions in DNA by O_3, which would be converted to strand breaks under the alkaline condition of the assay. Although these experiments do not prove that O_3 exposure can cause strand breaks in DNA, they do indicate an O_3 effect on DNA at 9800 µg/m^3 (5 ppm) of O_3 for 24 hr.

Because of the importance of the reports by Zelac et al. (1971a,b) that indicated that significant levels of chromosome aberrations in Chinese hamster peripheral blood lymphocytes collected as late as 15 days after O_3 exposure by inhalation, Tice et al. (1978) tried to repeat the experiments of Zelac as closely as possible. Chinese hamsters were exposed to 843 $\mu g/m^3$ (0.43 ppm) of O_3 by inhalation for 5 hr. The authors investigated chromatid and chromosome aberrations in peripheral blood lymphocytes and bone marrow of control and O_3-exposed animals immediately after exposure and at 7 and 14 days after O_3 exposure. They also investigated the sister chromatid exchange (SCE) frequency in peripheral blood lymphocytes of Chinese hamsters. In separate experiments, SCE frequencies in C57/Bl mice exposed to 2 ppm of O_3 for 6 hr were examined in peripheral blood cells collected from the animals immediately after O_3 exposure and at 7 and 14 days after O_3 exposure.

The authors reported no significant increase in the SCE frequency of the O_3-exposed hamsters or mice at any sampling time, nor did they observe a significant increase in the number of chromosome aberrations of phytohemagglutinin (PHA)-stimulated peripheral blood or bone marrow cells. The only reported statistically significant differences were observed in peripheral blood lymphocytes, in which there was an increase in the number of chromatid deletions and achromatic lesions in the 7 and 14 day samples, respectively. Both types of chromatid aberration were observed at consistently higher frequencies in the blood samples of the O_3-exposed animals, frequently in the range of 50 to 100 percent increases over the control values. Statistically significant differences were assigned at the 1 percent level of significance. It is not clear how a slightly less rigorous evaluation of significance (e.g., $p < 0.05$) would have influenced the interpretation of the data.

Although both Zelac et al. (1971a,b) and Tice et al. (1978) reported significant increases in chromosome aberrations in peripheral blood lymphocytes following 5-hr exposures to 392 to 843 $\mu g/m^3$ (0.2 to 0.4 ppm) of O_3, the types of lesions observed in the two studies were clearly different. Tice et al. observed chromatid-type lesions and no increase in the chromosome aberrations, whereas Zelac et al. reported a significant increase in the number of chromosome aberrations. There were a number of differences in the experimental protocols that may have produced the seemingly different results:

1. The animals were exposed to different concentrations of O_3. Zelac et al. (1971a) administered 470 to 590 $\mu g/m^3$ (0.24 to 0.3 ppm) of O_3 to Chinese hamsters for 5 hr, whereas Tice et al. (1978) exposed animals to an atmosphere of 840 $\mu g/m^3$ (0.43 ppm) of O_3.

2. Zelac stimulated peripheral blood lymphocytes into DNA synthesis with pokeweed mitogen, which is mainly a B-lymphocyte mitogen. In the experiments of Tice et al. (1978), lymphocytes were stimulated with PHA, which is a T-lymphocyte mitogen (Ling and Kay, 1975).
3. Zelac cultured lymphocytes with the mitogen in vitro for 3 days (72 hr), whereas Tice et al. cultured lymphocytes with mitogen for 52 hours.

Because of the longer incubation time with the mitogen in the experiments of Zelac et al. (1971a), lymphocytes may have converted chromatid type aberrations, like those reported by Tice et al. (1978), into chromosome aberrations with another round of DNA synthesis. Because the experiments of Zelac et al. and Tice et al. were conducted with peripheral blood lymphocytes stimulated by two different mitogens (pokeweed vs PHA), the cytogenetic consequences of O_3 exposure were examined in different populations of lymphocytes. If one of the populations of lymphocytes was more sensitive to O_3 than the other, different cytogenetic responses could be expected when PHA was used as a mitogen, compared with the results with the use of polkweed mitogen.

There is evidence that the B-lymphocyte may be more sensitive to O_3 than the T-lymphocyte. Savino et al. (1978) measured the effects of O_3 on human cellular and humoral immunity by measuring rosette formation with human lymphocytes (See Chapter 11). Rosette formation measures the reaction of antigenic red cells with surface membrane sites on lymphocytes. Different antigenic RBCs are used to distinguish T-lymphocytes from B-lymphocytes. Rosette formation with B-lymphocytes was significantly depressed in eight human subjects exposed to 784 $\mu g/m^3$ (0.4 ppm) of O_3 by inhalation for 4 hr. A similar inhibition of rosette formation was not observed with T-lymphocytes from the same subjects. The depressed B-cell responses persisted for 2 weeks after O_3 exposure, although partial recovery to the pre-exposure level was evident.

It cannot be stated with any certainty how the differences in the O_3 exposure, the choice of mitogen, and the length of the mitogen exposure may have contributed to the differences in the results reported by Zelac et al. (1971a,b) and by Tice et al. (1978). There are sufficient differences in the experimental protocols of the two reports so that the results need not be considered directly contradictory.

An assumption that is made in all of the reports in which lymphocytes are stimulated with mitogens is that the lymphocytes from the O_3-exposed animals and the control animals are equally sensitive to the mitogenic stimulus. This assumption is probably not correct, because in investigations by Peterson et al. (1978a,b) the proliferation of human lymphocytes exposed to PHA was significantly suppressed in blood samples taken immediately after the subjects were exposed to 784 $\mu g/m^3$ (0.4 ppm) of O_3 for 4 hr (See 11.7). Other reports have suggested that O_3 might inhibit or inactivate the PHA receptor on lymphocytes (see Gooch et al., 1976). Because the ability to measure chromosome aberrations in mitotically arrested cells is absolutely dependent on the induction of G_0 or G_1 cells into the cycling state, cells exposed to sufficient concentrations of O_3 would not be stimulated to divide, and hence no O_3-induced cytogenic effects would be observed in activated cells. In their report, Tice et al. (1978) stated that the lymphocytes of the O_3-exposed animals in their experiments "did tend to be worse than those from controls." Only a small difference in the number of responding lymphocytes could make large differences in the results of the experiments if O_3-damaged lymphocytes were selected against in the cytogenetic investigations.

In other investigations with rodents, Gooch et al. (1976) analyzed bone marrow samples from Chinese hamsters exposed to 451 $\mu g/m^3$ (0.23 ppm) of O_3 for 5 hr. Marrow samples were taken at 2, 6, and 12 hr following O_3 exposures. In separate experiments, male C_3H mice were exposed to 294 or 412 $\mu g/m^3$ (0.15 or 0.21 ppm) of O_3 for 5 hr, or to 1940 $\mu g/m^3$ (0.99 ppm) of O_3 for 2 hr. Blood samples were drawn from these animals at various times for up to 2 weeks following O_3 exposure. The mice were killed 8 weeks following O_3 exposure, and spermatocyte preparations were made and analyzed for reciprocal translocations. Data from the Chinese hamster bone marrow samples and the mouse leukocytes indicated that there was no effect induced by O_3 treatment on the frequency of chromatid or chromosome aberrations, nor were there any recognizable reciprocal translocations in the primary spermatocytes.

Several investigators have examined the effects of O_3 on human cells _in vitro_. Fetner (1962) observed the induction of chromatid deletions in human KB cells exposed to 15,680 $\mu g/m^3$ (8 ppm) of O_3 for 5 to 25 min. Sweet et al. (1980) reported that the growth of human cells from breast, lung, and uterine tumors was inhibited by exposure to 588 to 1568 $\mu g/m^3$ (0.3 to 0.8 ppm) of O_3 for 8 days in culture.

Guerrero et al. (1979) performed SCE analysis on diploid human fetal lung cells (WI-38) exposed to 0, 490, 980, 1470, or 1960 µg/m^3 (0, 0.25, 0.5, 0.75, or 1.0 ppm) O_3 for 1 hour in vitro. A dose-related increase in the SCE frequency was observed in the WI-38 human fibroblasts exposed to O_3. In the same report, the authors stated that no significant increase in the SCE frequency over control values was observed in peripheral blood lymphocytes from subjects exposed to O_3 by inhalation (Chapter 11). Unless the lymphocyte is intrinsically less sensitive to the induction of SCE by O_3 than the WI-38 human fetal lung fibroblast, the results indicate that exposure of human subjects to 980 µg/m^3 (0.5 ppm) of O_3 for 2 hr did not result in a sufficiently high concentration of O_3 or O_3 reaction products in the circulation to induce an increase in the SCE frequency in the lymphocytes. From the authors' data on the induction of SCE in WI-38 cells, the concentration of O_3 required to induce SCE in human cells is approximately 490 µg/m^3 (0.25 ppm) for 1 hour.

Gooch et al. (1976) also investigated the effects of O_3 exposure on human cells in vitro. In these experiments, lymphocytes were stimulated with PHA for 12 or 36 hr before the O_3 exposure to obviate the potential problems of O_3 inactivation of the PHA receptor. Human leukocyte cultures were exposed to 3920 µg/m^3 (2 ppm) of O_3 for various lengths of time to accumulate total O_3 exposure doses of 3234 to 27,832 µg/m^3 per hour (1.65 to 14.2 ppm/hr). The results showed no increase in the chromatid and chromosome aberrations at any total dose, with the possible exception of an apparent spike in chromatid aberrations at a total exposure of 14,170 µg/m^3 (7.23 ppm/hr). The significance of this observation is unclear because the data showed no dose-response increase in the number of chromatid aberrations at concentrations near 7.25 ppm/hr, and the authors did not report how, or indeed if, the data were statistically evaluated for differences in chromatid aberrations.

In summary, in vitro O_3 exposure has been shown to produce toxic effects on cells and cellular components including the genetic material. Cytogenetic toxicity has been reported in cells in culture and in cells isolated from animals if O_3 exposure has occurred at sufficiently high levels and for sufficiently long periods.

10.4.5.2 Mutational Effects of Ozone. The mutagenic effects of O_3 have been investigated in surprisingly few instances (Table 10-24). No publication to date has investigated the mutagenic effects of O_3 in mammalian cells.

Sparrow and Schairn (1974) measured an increase in the frequency, over the background level, in the induction of pink or colorless mutant cells or groups of cells in petal and/or stamen hairs of mature flowers of various blue-flowered Tradescantia. No O_3 concentration was reported in this publication.

E. coli, strain MQ 259, were mutated to various growth factor auxotrophic states, including requirements for most common amino acids, vitamins, and purines and pyrimidines (Hamelin and Chung, 1975a). Ozonated air 196 µg/m^3, 0.1 ppm) was passed through the bacterial suspensions at a rate of 2.1 L/min for 30 min. Many of the O_3-induced mutant strains were either more or less sensitive to UV light than the parental strain. Other mutant strains, called mucoid mutants, had apparent defects in DNA repair pathways and were characterized (Hamelin and Chung, 1975b) as producing excessive amounts of capsular polysaccharide.

Erdman and Hernandez (1982) investigated the induction of dominant lethal mutations in Drosophila virilis exposed to 58,800 µg/m^3 (30 ppm) of O_3 for 3 hr. O_3 induced dominant lethal mutations at various stages of spermatogenesis. The sperm-sperm bundle stage was the most sensitive to O_3, and the meiotic cells were the least sensitive.

Dubeau and Chung (1979, 1982) have investigated the mutagenic and cytotoxic effects of O_3 on Saccharomyces cerevisae. Several different strains were utilized to investigate forward, reverse, and recombinational mutations. ozone (98,000 µg/m^3, 50 ppm; 30 to 90 min) induced a variety of forward and reverse mutations as well as gene conversion and mitotic crossing-over. Both base-substitution and frame-shift mutations were induced by O_3. Ozone was shown to be more recombinogenic than mutagenic in yeast, probably as a result of the induction of strand breaks in DNA, either directly or indirectly.

In the investigation of Dubeau and Chung (1982), the mutagenic potency of O_3 (98,000 µg/m^3, 50 ppm; 30 to 90 min) was compared with other known mutagens. The positive controls were UV light (1.54 J/m^2 per second, 1-min exposure), N-methyl-N'-nitrosoguanidine (MNNG) (50 µg/mL, 15 min), or x-rays (2 kR/ min, 40 min). By comparing the induced mutation frequency at similar cellular survival levels for O_3, MNNG, UV light, and x-rays, it was shown that O_3 was a very weak mutagen. Induced mutation frequencies were generally 20 to 200 times lower for O_3 than for the other three mutagens.

In summary, the mutagenic properties of O_3 have been demonstrated in procaryotic and eucaryotic cells. Only one study, however, (Hamelin and Chung, 1975a, with E. coli) investigated the mutagenic effect of O_3 at concentrations of less than 1 ppm. The results clearly indicate that if cells in culture are exposed to sufficiently high concentrations of O_3 for sufficiently long periods, mutations will result. The relevance of the presently described investigations to human or even other mammalian mutagenicity is not apparent. Additional studies with human and other mammalian cells will be required before the mutagenic potency of O_3 toward these species can be determined.

10.4.6 Other Extrapulmonary Effects

10.4.6.1 Liver. A series of studies reviewed by Graham et al. (1983a) have shown that O_3 increases drug-induced sleeping time in animals (Table 10-25). The animal was injected with the drug (typically pentobarbital), and the time to the loss of the righting reflex and the sleeping time (time between loss and regaining of the righting reflex) were measured. Because the time to the loss of the righting reflex was very rarely altered in the experiments described below, it will not be discussed further. Animals awake from pentobarbital-induced sleeping time, because liver xenobiotic metabolism transforms the drug into an inactive form. Therefore, this response is interpreted as an extrapulmonary effect.

Gardner et al. (1974) were the first to observe that O_3 increases pentobarbital-induced sleeping time. Female CD-1 mice were exposed for 3 hr/day for up to 7 days to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 and the increase was found on days 2 and 3 of exposure, with the greatest response occurring on day 2. Complete tolerance did not occur; when mice were pre-exposed (1960 $\mu g/m^3$, 1.0 ppm; 3 hr/day for 7 days) and then challenged with a 3-hr exposure to 9800 $\mu g/m^3$ (5.0 ppm) on the eighth day, pentobarbital-induced sleeping time increased greatly.

A series of follow-up studies was conducted to characterize the effect further. To evaluate female mouse strain sensitivity, one outbred (CD-1) and two inbred (C57BL/6N and DBA/2N) strains were compared (Graham et al., 1981). Ozone (1960 $\mu g/m^3$, 1.0 ppm for 5 hr) increased pentobarbital-induced sleeping time in all strains. To determine whether this effect was sex- or species-specific, male and female CD-1 mice, rats, and hamsters were exposed for 5 hr to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 (Graham et al., 1981). The females of all

TABLE 10-25. EFFECTS OF OZONE ON THE LIVER

Ozone concentration		Measurement[a,b] method	Exposure duration and protocol	Observed effects(s)	Species	Reference
$\mu g/m^3$	ppm					
196- 9800	0.1- 5	CHEM GPT	3 hr/day, 1-17/days	Increase in pentobarbital-induced sleeping time with following exposure regimens; 0.1 ppm, 15 or 16 days; 0.25 ppm, 6 or 7 days; 0.5 ppm, 2 or 3 days; 1 ppm, 1, 2, or 3 days; 5 ppm, 1 day. No effects at days before or after days given above.	Mouse (female)	Graham et al., 1981
588	0.3	UV	3 hr	No effect on liver reduced ascorbic acid levels.	Rat	Calabrese et al., 1983c
1470 5880 19,600	0.75 3 10	NBKI	3 hr	No effect on hepatic benzo(a)pyrene hydroxylase activity.	Hamster	Palmer et al., 1971
1600 (max)	0.82 (max)	UV	4 hr (max)	Decrease in hepatic reduced ascorbic acid content. Actual exposure regimens not reported, only maximal levels given.	Mouse	Veninga et al., 1981
1960	1	ND	3 hr/day	Increase in pentobarbital-induced sleeping time after 2 or 3 days, but not other days (up to 7 days). No tolerance to a challenge of O_3 ($9800\ \mu g/m^3$, 5 ppm x 3 hr) to mice pre-exposed to 1 ppm for 7 days.	Mouse (female)	Gardner et al., 1974
1960	1	CHEM GPT	5 hr	Increase in pentobarbital-induced sleeping time in 3 strains of female mice (CD-1, C57BL, and DBA), female rats, and male and female hamsters. Male mice and rats not affected, even when male mice received 3 days (5 hr/day) of exposure. The increase in male hamsters was less than the increase in female hamsters.	Mouse, rat, hamster (male and female)	Graham et al., 1981

TABLE 10-25. EFFECTS OF OZONE ON THE LIVER (continued)

Ozone concentration μg/m³	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effects(s)	Species	Reference
1960	1	CHEM GPT	5 hr/day, 1,2,3 or 4 days	Increase in pentobarbital-induced sleeping time at 1,2, and 3 days, decreased with increasing days of exposure. 24-hr postexposure for each group, no effects occurred.	Mouse (female)	Graham et al., 1981
1960	1	CHEM GPT	5 hr	Increase in hexobarital-and thiopental-induced sleeping time and zoxazolamine-induced paralysis time. Pretreatment with mixed function oxidase inducers (phenobarbital, pregneolone -16a-carbonitrile, and β-naphthoflavone, but not pentobarbital) decreased phenobarbital-induced sleeping time in CD-1 mice, and O_3 increased the sleeping time in all groups. Pretreatment with inhibitors (SF525A, piperonyl butoxide) reduced the sleeping time, but O_3 increased the sleeping time, with the magnitude of the increase becoming larger as the dose of inhibitor was increased.	Mouse (female)	Graham et al., 1982a
1960 9800	1 5	CHEM GPT	5 hr 3 hr	No effect on hepatic cytochrome P-450 concentration, aminopyrine N-demethylase, or p-nitroanisole O-demethylase activities. Aniline hydroxylase activity increased at 5 ppm (3 hr) and at 1 ppm (5 hr/day x 2 days). No change in liver to body weight ratios.	Mouse (female)	Graham et al., 1982b

TABLE 10-25. EFFECTS OF OZONE ON THE LIVER (continued)

Ozone concentration µg/m³	Ozone concentration ppm	Measurement[a,b] method	Exposure duration and protocol	Observed effects(s)	Species	Reference
1960 9800	1 5	CHEM GPT	5 hr	At 1 ppm: 71% increase in plasma half-life of pentobarbital, decrease ($p = 0.06$) in slope of clearance curve. At 5 ppm: 106% increase in plasma half-life of pentobarbital; decrease in slope of clearance curve; no effect on concentrations of pentobarbital in brain at time of awakening; no change in type of pentobarbital metabolites in serum/or brain.	Mouse (female)	Graham 1979; Graham et al., 1983a,b
1960	1	ND	90 min	No effect on hepatic cytochrome P-450 concentration.	Rabbit	Goldstein et al., 1975
3920	2	UV	8 hr/day	Supplementing or depriving rats of vitamin E or selenium altered the O_3 effect. O_3 caused changes in several *in vitro* enzyme activities in the liver and kidney (see text).	Rat	Reddy et al., 1983

[a] Measurement method: CHEM = gas-phase chemiluminescence; NBKI = neutral buffered potassium iodide; UV = UV photometry; ND = not described

[b] Calibration method: GPT = gas phase titration

species exhibited an increased pentobarbital-induced sleeping time. Male mice and rats were not affected. Male hamsters had an increase in sleeping time, but this increase was less ($p = 0.075$) than the increase observed in the females. Thus, the effect is not specific to strain of mouse or to three species of animals, but it is sex-specific, with females being more susceptible. Female CD-1 mice were exposed to 196 to 9800 $\mu g/m^3$ (0.1 to 5.0 ppm) of O_3 for 3 hr/day for a varying number of days (Graham et al., 1981). At 1960 $\mu g/m^3$ (1.0 ppm), effects were observed after 1, 2, or 3 days of exposure, with the largest change occurring on day 2. At 980 $\mu g/m^3$ (0.5 ppm), the greatest increase in pentobarbital-induced sleeping time was observed on day 3, but at 490 $\mu g/m^3$ (0.25 ppm), 6 days of exposure were required to cause an increase. At the lowest concentration evaluated (196 $\mu g/m^3$, 0.1 ppm), the increase was only observed at days 15 and 16 of exposure. Thus, as the concentration of O_3 was decreased, increasing numbers of daily 3-hr exposures were required to significantly increase pentobarbital-induced sleeping time. Once the maximal effect occurred, increasing the number of exposures resulted in a diminution of the effect. Generally, effects were observed around an approximate C X T (concentration, ppm x time, hr) value of 5. Also, CD-1 female mice were exposed to four different concentrations of O_3 (1960 to 196 $\mu g/m^3$, 1.0 to 0.1 ppm) for 5 to 20 hr continuously in a fashion yielding a C x T value of 5 (Graham et al., 1981). All regimens increased pentobarbital-induced sleeping time. The time to recovery was examined in mice exposed to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 for 5 hr/day. Recovery was complete within 24 hr after exposure, whether exposure was for 1, 2, or 3 days.

To determine whether the previous responses were specific to pentobarbital, other drugs with known and different mechanisms for termination of action were used in CD-1 female mice exposed to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 for 5 hr (Graham et al., 1982a). Ozone increased sleeping time induced by hexobarbital and thiopental and paralysis time induced by zoxazolamine. Within the liver, pentobarbital and hexobarbital metabolism is more related to cytochrome P-450 than to cytochrome P-448-dependent activities. Zoxazolamine metabolism is more related to cytochrome P-448 than to cytochrome P-450. Other major differences in the nature of the metabolism (i.e., aliphatic vs. aromatic) also exist between these three drugs. In contrast to the above, sedation from thiopental is terminated because of drug redistribution. Thus, it would appear that O_3 might affect some aspects of both drug redistribution and metabolism. Although there are different mechanisms involved in hexobarbital, zoxazolamine, and pentobarbital metabolism, it is possible that some common component(s) of metabolism may have been altered.

CD-1 female mice were pretreated with mixed-function oxidase inducers and inhibitors with partially characterized mechanisms of action to relate any potential differences in the effect of O_3 to differences in the actions of the agents. Mice were exposed to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 or air for 5 hr before measurement of pentobarbital-induced sleeping time (Graham et al., 1982a). Again, the effect of O_3 was observed, but mechanisms were not elucidated.

The effect of O_3 on hepatic mixed-function oxidases in CD-1 female mice was evaluated in an attempt to relate to the sleeping time studies (Graham et al., 1982b). A 3-hr exposure to concentrations of O_3 as high as 9800 $\mu g/m^3$ (5.0 ppm) did not change the concentration of cytochrome P-450 or the activities of related enzymes (aminopyrine N-demethylase or p-nitroanisole O-demethylase). However, this exposure regimen and another (1960 $\mu g/m^3$, 1.0 ppm, 5 hr/day for 2 days) increased slightly the activity of another mixed-function oxidase, aniline hydroxylase. Goldstein et al. (1975) also found no effect of a 90-min exposure to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 on liver cytochrome P-450 levels in rabbits. Hepatic benzo(a)pyrene hydroxylase (another mixed-function oxidase) activity of hamsters was unchanged by a 3-hr exposure to up to 19,600 $\mu g/m^3$ (10 ppm) of O_3 (Palmer et al., 1971).

Pentobarbital pharmacokinetics in female CD-1 mice were also examined. A 3-hr exposure to 9800 $\mu g/m^3$ (5.0 ppm) of O_3 did not affect brain concentrations of pentobarbital at time of awakening, even though sleeping time was increased (Graham, 1979). Therefore, it appears that O_3 did not alter the sensitivity of brain receptors to pentobarbital. A similar exposure regimen also did not alter the pattern of brain or plasma metabolites of pentobarbital at various times up to 90 min postexposure (Graham, 1979). Following this exposure, first-order clearance kinetics of pentobarbital were observed in both the air and O_3 groups, and O_3 increased the plasma half-life by 106 percent (Graham, 1979). Mice exposed to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 for 5 hr had a 71 percent increase in the plasma half-life of pentobarbital (Graham et al., 1983b). This ozone exposure resulted in a decrease ($p = 0.06$) in the slope of the clearance curve. Clearance followed first-order kinetics with a one-compartment model in this experiment also.

In summary, the mechanism(s) for the effect of O_3 on pentobarbital-induced sleeping time are not known definitively. However, it is hypothesized (Graham et al., 1983a) that some common aspect(s) of drug metabolism is quantitatively reduced, whether it is direct (e.g., enzymatic) or indirect (e.g., liver blood flow) or a combination of both. In addition, drug redistribution is apparently slowed. It is unlikely that ozone itself caused these effects at target sites distant from the lung (see Section 10.2). Because of the free-radical nature of oxidation initiated by O_3, a myriad of oxygenated products, several of which have toxic potential, may be formed in the lung (Section 10.3.3). However, the stability of such products in the blood and their reaction with organs such as the liver are speculative at present.

Reddy et al. (1983) studied the effects of a 7-day (8 hr/day) exposure of rats to 3920 $\mu g/m^3$ (2.0 ppm) of O_3 on liver xenobiotic metabolism by performing *in vitro* enzyme assays. Although lower O_3 levels were not tested, this study is presented because it indicates the potential of O_3 to cause hepatic and kidney effects. The rats used were either supplemented or deficient in both vitamin E and selenium. Ozone exposure caused a decrease in microsomal cytochrome P-450 hydroperoxidase activity in livers of rats deficient in both substances, whereas an increase resulted in the supplemented animals. Rats deficient in vitamin E and selenium experienced a decrease in liver microsomal epoxide hydrolase activity after O_3 exposure; no effect was observed in supplemented rats. Glutathione S-transferase activity was increased in the liver and kidney in both the supplemented and deficient groups. Selenium-independent glutathione peroxidase activity was not significantly affected in the livers of the supplemented or deficient rats. However, O_3 decreased selenium-dependent glutathione peroxidase activity in the livers of supplemented rats and caused an increase in deficient rats. In the kidney, both these groups of animals had an increase in this enzyme activity. Other groups of rats (deficient in vitamin E, supplemented with selenium; supplemented with vitamin E, deficient in selenium) were examined also and in some cases, different results were observed. The authors interpreted these results (along with pulmonary effects) as a compensatory mechanism to protect cells from oxidants. A more extensive interpretation of the effects depends on the nutritional status and the presence of other compounds metabolized by the affected enzymes. For example, epoxide hydrolase, which was decreased in the vitamin E- and selenium-deficient rats, metabolizes reactive epoxides to dihydrodiols. The metabolism of a substance such as benzo(a)pyrene would be expected to be affected by such a change. However, because of the complexity of the metabolism of a given chemical, such as benzo(a)pyrene, a precise interpretation is not possible at this time.

Veninga et al. (1981) exposed mice to O_3 and evaluated hepatic reduced ascorbic acid content. The authors expressed the exposure regimen in the form of a C x T value from about 0.2 to 3.2. Actual exposure regimes cannot be determined. They stated that the maximal O_3 level was 1600 $\mu g/m^3$ (0.82 ppm) and the maximal exposure time was 4 hr, which would have resulted in a C x T of about 3.2. Animals were studied at 0, 30, and 120 min postexposure. It appeared that immediately after exposure, a C x T value < 0.4 caused a decrease in the reduced ascorbic acid content of the liver. At a C x T value of 0.4 and 0.8, there appeared to be an increase that was not observed at higher values. For the 30-min postexposure groups, the increase in reduced ascorbic acid shifted, with the greatest increase being at about a C x T value of 1.2 and no change occurring at a C x T value of 2.0. The 120-min postexposure group was roughly similar to the immediate post-exposure group. No effects occurred 24 hr postexposure.

Hepatic reduced ascorbic acid levels were also studied by Calabrese et al. (1983c) in rats exposed for 3 hr to 588 $\mu g/m^3$ (0.3 ppm) of O_3 and examined at 5 postexposure periods up to 24 hr. Rats had significantly increased ascorbic acid levels in both the O_3 and air groups, with the greater change taking place in the air group. Thus, there were no changes due to O_3. Likewise, there was no O_3 effect on reduced ascorbic acid content in the serum.

10.4.6.2 The Endocrine System. A summary of the effects of O_3 on the endocrine system, gastrointestinal tract, and urine is given in Table 10-26. Fairchild and co-workers were the first to observe the involvement of the endocrine system in O_3 toxicology. Mice exposed to 11,368 $\mu g/m^3$ (5.8 ppm) for 4 hr were protected against mortality by α - naphthylthiourea (ANTU) (Fairchild et al., 1959). Because ANTU has antithyroidal activity and can alter adrenal cortical function, Fairchild and Graham (1963) hypothesized a possible interaction of O_3 with the pituitary-thyroid-adrenal axis. In exploring the hypothesis, they exposed mice and rats for 3 to 4 hr to unspecified lethal concentrations of O_3. Thyroid-blocking agents and thyroidectomy increased the survival of mice and rats acutely exposed to O_3, and injections of the thyroid hormones, thyroxine (T_4), or triodothyronine (T_3) decreased their survival. This response in animals with altered thyroid function was not specific to a

TABLE 10-26. EFFECTS OF OZONE ON THE ENDOCRINE SYSTEM, GASTROINTESTINAL TRACT, AND URINE

Ozone concentration		Measurement[a] method	Exposure duration and protocol	Observed effect(s)[b]	Species	Reference
µg/m³	ppm					
5.4 21 110	0.003 0.01 0.056	c	93 days, continuous	From 6th wk to end of exposure, 0.056 ppm increased the urine concentration of 17-ketosteroids. After 93 days of exposure to 0.056 ppm, the ascorbic and level of the adrenal glands was decreased. No data were presented for these effects.	Rat	Eglite, 1968
490 2940	0.25 1.5	d	2 hr 30 min	1.5 ppm of O_3 (30 min) inhibited gastric mortality; recovery was rapid. The lower level caused no effects.	Rat 1972.	Roth and Tansy,
980 1960	0.5 1	I	5 hr/day, 4 days	No effects on thyroid release of ^{131}I, 96-384 hr post ^{131}I injection.	Rat 1964.	Fairchild et al.,
1470	0.75	ND	4-8 hr	LM and TEM changes in parathyroid glands. Loss of "clusterlike" arrangement of parenchyma. Dilated capillaries. Vacuolated chief cells. Increased RER, prominent Golgi, abundant secretory granules.	Rabbit	Atwal and Wilson, 1974
1470	0.75	ND	48 hr postexposure 1-20 days	Early postexposure parathyroid glands enlarged and congested with focal vasculitis. After 7 days postexposure, parenchymal atrophy, leukocyte infiltration and capillary proliferation. Authors suggest lesions may be due to autoimmune reactions.	Rabbit	Atwal et al., 1975
1470	0.75	ND	48 hr postexposure 12-18 days	Microvascular changes in the parathyroid glands, including hemorrhage, endothelial proliferation, platelet aggregation, and lymphocyte infiltration.	Dog	Atwal and Pemsingh, 1981
1568-2940 (range)	0.8-1.5 (range)	NBKI	6 hr/day, 4 days/wk about 19 wk	Lower titratable acidity of urine, with no changes in levels of creatine, uric acid/creatinine, amino acid nitrogen/creatinine, or excretion of 12 amino acids.	Rat 1962	Hathaway and Terrill,

TABLE 10-26. EFFECTS OF OZONE ON THE ENDOCRINE SYSTEM, GASTROINTESTINAL TRACT, AND URINE (continued)

Ozone concentration µg/m³	Ozone concentration ppm	Measurement[a] method	Exposure duration and protocol	Observed effect(s)[b]	Species	Reference
1960 3920 7840	1 2 4	I	5 hr	Decreased release of ^{131}I from thyroid, 48-384 hr post ^{131}Injection to all O_3 levels above 1 ppm.	Rat	Fairchild et al., 1964.
1960	1	ND	24 hr	Decreased serum level of thyroid-stimulating hormone from anterior pituitary, thyroid hormones (T_3, T_4, and free T_4), and protein-bound iodine; no change in unsaturated binding capacity of thyroid-binding globulin in serum; increase in prolactin levels; no change in levels of corticotropin, growth hormone, luteinizing hormone, follicle stimulating hormone from pituitary or insulin. Thyroidectomy prevented the effect on TSH levels. There was no effect on the circulating half-life of ^{131}I-TSH. The anterior pituitaries had fewer cells, but more TSH/cell. The thyroid gland was also altered. Exposures to between 0.2 to 2 ppm for unspecified lengths of time up to a potential maximum of 500 hr also caused a decrease in TSH levels.	Rat	Clemons and Garcia, 1980a,b.
79,800	> 5.0	I	> 3 hr < 8 hr	Anti-thyroid agents, thyroidectomy, hypophysectomy, and adrenalectomy protected against O_3-induced mortality. Injection of thyroid hormones decreased survival after O_3 exposure.	Mouse, rat	Fairchild et al., 1959; Fairchild and Graham, 1963; Fairchild, 1963.
9800	5	CHEM	3 hr	Increased levels of 5-hydroxytryptamine in lung; decreases in brain; no change in kidney.	Rat	Suzuki, 1976.

[a] Measurement method: CHEM = gas phase chemiluminescence; NBKI = neutral buffered potassium iodide; I = iodometric (Byers and Saltzman, 1956); ND = not described.

[b] Abbreviations used: LM = light microscopy; TEM = transmission electron microscopy; RER = rough endoplasmic reticulum; T_3 = triiodothyronine; T_4 = thyroxine.

[c] Spectrophotometric technique (dihydroacridine).

[d] Flow rates from ozonator.

concomitant altered metabolic rate, because another drug (dinitrophenol), which increases metabolism, had no effect on the O_3 response.

Hypophysectomy and adrenalectomy also protected against O_3-induced mortality, presumably in rodents (Fairchild, 1963). Hypophysectomy would prevent the release of thyroid stimulating hormone, thereby causing a hypothyroid condition as well as preventing the release of adrenocorticotropic hormone (ACTH), which would cause a decreased stimulation of the adrenal cortex to release hormones. This confirms the above-mentioned finding of thyroid involvement in O_3 toxicity and suggests that a decrease in adrenocorticosteroids reduces O_3 toxicity. Rats that have been adrenalectomized and treated with adrenergic blocking agents are more resistant to O_3 than rats that have only been adrenalectomized, indicating that decreases in catecholamines reduce O_3 toxicity.

Potential tolerance to the effect of O_3 on thyroid activity was also investigated by Fairchild et al. (1964). A variety of exposure regimens were used for the rats, and the release of ^{131}I was used as an index of thyroid function. A 5-hr exposure to 1960, 3920, or 7840 $\mu g/m^3$ (1, 2, or 4 ppm) of O_3 inhibited the release of ^{131}I at several time periods post injection of ^{131}I (48, 96, 192, and 384 hr). The rats were injected before the 5-hr exposure, presumably shortly before exposure. Twenty-four hr post-injection, only the highest O_3 concentration showed an effect. Rats were also exposed for 5 hr/day for 4 days to either 980 or 1960 $\mu g/m^3$ (0.5 or 1.0 ppm) of O_3. At 96, 192, and 384 hr post-injection of ^{131}I, no effects were observed. Thus, tolerance appeared to have occurred, a finding consistent with lethality studies with O_3 (Matzen, 1957a). In another study, rats were exposed to 3920 $\mu g/m^3$ (2.0 ppm) of O_3 5 hr/day for 2 days and challenged with a 5-hr exposure to 7840 $\mu g/m^3$ (4.0 ppm) on the third day. These animals exhibited a greater effect than rats that received only the 7840-$\mu g/m^3$ (4.0 ppm) challenge. This difference persisted for 48, 96, and 192 hr post-injection. Thus, although it appears that tolerance occurs, it results in a condition that leads to stimulation of thyroid activity after a subsequent exposure to an O_3 challenge.

Clemons and Garcia (1980a,b) extended this area of research by investigating the effects of O_3 on the hypothalamo-pituitary-thyroid axis of rats. Generally, these three endocrine organs regulate the function of each other through complex feedback mechanisms. Either stimulation or inhibition of the hypothalamus regulates the release of thyrotropin-releasing hormone (TRH). The thyroid hormones (T_3 and T_4) can stimulate TRH. Thyrotropin-releasing hormone and circulating thyroid hormones (T_3 and T_4) regulate secretion of thyroid-stimulating hormone (TSH) from the anterior pituitary. Stimulation of the thyroid by TSH releases T_3 and T_4. A 24-hr exposure to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 caused decreases in the serum concentrations of TSH, T_3, T_4, free T_4, and protein-bound iodine. There was no change in the uptake of T_3, and thus no change in the unsaturated binding capacity of thyroid-binding globulin in the serum. Prolactin levels were increased also, but no alterations were observed in the concentrations of other hormones (corticotropin, growth hormone, luteinizing hormone, follicle stimulating hormone, and insulin). Plasma TSH was also evaluated after continuous exposures to between 392 and 3920 $\mu g/m^3$ (0.2 and 2.0 ppm) for unspecified lengths of time in a fashion to result in a concentration x time relationship between about 2 and 100. Plasma TSH was decreased after a C x T exposure of about 6. These data cannot be independently interpreted, because the specific exposure regimens were not given. The authors state, without any supporting data, that the decrease in TSH levels persisted "beyond two weeks" when exposure was continued. Therefore, it appears that tolerance may not have occurred. Thyroidectomized rats exposed to 1960, 3920, 5880 or 7840 $\mu g/m^3$ (1.0, 2.0, 3.0, or 4.0 ppm) of O_3 for 24 hr did not exhibit a decrease in the levels of TSH. Exposure to (presumably) 1960 $\mu g/m^3$ (1.0 ppm) for 24 hr did not alter the circulating half-life of ^{125}I-labeled TSH injected into the rats, and therefore, there apparently is no effect on TSH once it is released from the pituitary.

To evaluate pituitary function further, rats exposed 24 hr to 1960 $\mu g/m^3$ (1.0 ppm) of ozone were immediately subjected to a 45-min exposure to the cold (5°C) (Clemons and Garcia, 1980a,b). The anterior pituitary released an increased level of TSH, indicating that the hypothalamus was still able to respond (via increased TRH) after O_3 exposure. The increase was greater in the O_3 group, which might indicate increased production of TRH or increased sensitivity to TRH. In addition, the anterior pituitaries of the O_3 group had fewer cells than the air group. The cells from the O_3-exposed rats had more TSH and prolactin per 1000 cells, irrespective of whether the cells had received a TRH treatment. The cells from the O_3 group also released a greater amount of TSH, but not prolactin, into the tissue culture medium.

The thyroid gland itself was altered by the O_3 exposure (apparently 1960 $\mu g/m^3$, 1.0 ppm, for 24 hr). Ozone increased thyroid weight without changing protein content (e.g., edema) and decreased the release of T_4 per milligram of tissue. There was no change in T_4 release per gland. Clemons and Garcia (1980a,b) interpreted these findings as an O_3-induced lowering of the hypothalamic set point for the pituitary-thyroid axis and a simultaneous reduction of prolactin inhibiting factor activity in the hypothalamus.

The susceptibility of the parathyroid gland to O_3 exposure was investigated by Atwal and co-workers. In the initial study (Atwal and Wilson, 1974), rabbits were exposed to 1470 $\mu g/m^3$ (0.75 ppm) of O_3 for 4 to 8 hr, and the parathyroid gland was examined with light and electron microscopy at 6, 18, 22, and 66 hr after exposure. The parathyroid gland exhibited increased activity after O_3 exposure. Changes included hyperplasia of chief cells; hypertrophy and proliferation of the rough endoplasmic reticulum, free ribosomes, mitochondria, Golgi complex, and lipid bodies; and an increase of secretion granules within the vascular endothelium and capillary lumen. Such changes suggested an increased synthesis and release of parathormone, but actual hormone levels were not measured.

Atwal et al. (1975) also investigated possible autoimmune involvement in parathyroiditis of rabbits following a 48-hr exposure to 1470 $\mu g/m^3$ (0.75 ppm) of O_3. The authors stated that there was both a "continuous" and an "intermittent" 48-hr exposure, without specifying which results were due to which exposure regimen. Animals were examined between 1 and 20 days postexposure. Hyperplastic parathyroiditis was observed to be followed by capillary proliferation and leukocytic infiltration. Cytologic changes included the presence of eosinophilic leukocytes, reticuloendothelial and lymphocytic infiltration, disaggregation of the parenchyma, and interstitial edema. A variety of alterations were observed by electron microscopy, including atrophy of the endoplasmic reticulum of the chief cells, atrophy of mitochondria, degeneration of nuclei, and proliferation of the venous limb of the capillary bed. The alterations to the parathyroid gland were progressive during postexposure periods. Parathyroid-specific autoantibodies were detected in the serum of O_3-exposed rabbits, suggesting that the parathyroiditis might be due to inflammatory injury with an autoimmune causation. The microvascular changes were further studied by Atwal and Pemsingh (1981) in dogs exposed to 1470 $\mu g/m^3$ (0.75 ppm) of O_3 for 48 hr. They reported focal hemorrhages, vascular endothelial proliferation, intravascular platelet aggregation, and lymphocytic infiltration. A potential autoimmunity after O_3 exposure was also observed by Scheel et al. (1959), who showed the presence of circulating antibodies against lung tissue.

Also classed as a hormone is 5-hydroxytryptamine (5-HT), and it too interacts with O_3 toxicity (Suzuki, 1976). It has a variety of activities, including bronchoconstriction and increased capillary permeability; it can be a neurotransmitter. Although rats were exposed to a high concentration (9800 $\mu g/m^3$, 5.0 ppm) of O_3 for 3 hr, this study is discussed because extrapulmonary effects were observed. This exposure caused an increase in the 5-HT content of the lung and spleen, a decrease in 5-HT in the brain, and no change in the levels of 5-HT in the liver or kidney.

Adrenal cortex function after a 93-day (continuous) exposure to O_3 was investigated in rats (Eglite, 1968). Exposure to 110 $\mu g/m^3$ (0.056 ppm), but not lower levels, increased the urine concentration of 17-ketosteroids from the 6th week of exposure to the end of exposure. There was also a decrease in ascorbic acid in the adrenals. The generation and monitoring methods for the O_3 exposures were not sufficiently described. The authors described the effects as statistically significant but did not specify the statistical methods. No data were provided. Therefore, these results need to be confirmed before accurate interpretation is possible.

10.4.6.3 Other Effects. Rats were exposed for 6 hr/day, 4 days/week, for about 19 weeks, and analyses were performed on urine collected for the 16 hr following the exposure week (Hathaway and Terrill, 1962). Ozone exposures were relatively uncontrolled, ranging from 1568 to 2940 (0.8 to 1.5 ppm). All parameters were not measured for each week of exposure. On days 91 and 112 after initial exposure, there was a lower titratable acidity and higher pH in the urine of O_3-exposed animals. Titratable acidity was also lower on day 98. Ozone did not alter the levels of creatinine, creatine, uric acid/ creatinine, amino acid nitrogen/creatinine excretions, or excretion of 12 amino acids. The lungs and kidneys were examined histologically, and no consistent differences were observed. The authors interpreted the results as a reflection of respiratory alkalosis, assuming no kidney toxicity.

Gastric secreto-motor activities of the rat were investigated by Roth and Tansy (1972). A 2-hr exposure to 490 $\mu g/m^3$ (0.25 ppm) caused no effects. Thirty minutes of exposure to 2940 $\mu g/m^3$ (1.5 ppm) inhibited gastric motility, but activity tended to return towards normal for the remaining 90 min of exposure. Recovery had occurred by 20 min postexposure. However, these results are questionable because ozone was monitored only by ozonator flow rates.

10.5 EFFECTS OF OTHER PHOTOCHEMICAL OXIDANTS

10.5.1 Peroxyacetyl Nitrate

Very little information on the toxicity of peroxyacetyl nitrate (PAN) has appeared in the literature since the previous criteria document on photochemical oxidants (U.S. Environmental Protection Agency, 1978). The document reviewed the results of inhalation experiments with mice that tested PAN's lethal concentration (LC_{50}) (Campbell et al., 1967), its effects on lung structure (Dungworth et al., 1969); and its influence on susceptibility to pulmonary bacterial infections (Thomas et al., 1977). The concentration of PAN used in these studies ranged from 22.3 mg/m^3 (4.5 ppm) to 750 mg/m^3 (150 ppm). They are considerably higher than the 0.174 mg/m^3 (0.037 ppm) daily maximum concentration of PAN reported for ambient air samples in areas having relatively high oxidant levels (Chapter 6) and are of questionable relevance to the assessment of effects on human health.

Campbell et al. (1967) estimated that the LC_{50} for mice ranged from 500 to 750 mg/m^3 (100 to 150 ppm) for a 2-hr exposure to PAN at 80°F (25°C). Mice in the 60- to 70-day-old age group were more susceptible to PAN lethality than mice ranging from 98 to 115 days in age. Temperature also influenced the lethal toxicity of PAN; a higher LC_{50} (less susceptibility) was seen at 70°F (125 ppm) than at 90°F (85 ppm). In a follow-up study, Campbell et al. (1970) characterized the behavioral effects of PAN by determining the depression of voluntary wheel-running activity in mice. Exposures to 13.9, 18.3, 27.2, 31.7, and 42.5 mg/m^3 (2.8, 3.7, 5.5, 6.4, and 8.6 ppm) of PAN for 6 hr depressed both the 6-hr and 24-hr activity when compared to similar pre-exposure periods. Depression was more complete and occurred more rapidly with higher exposure levels. However, the authors indicated that PAN was less toxic than O_3 when compared to similar behavioral data reported by Murphy et al. (1964) (Section 10.4.1).

Dungworth et al. (1969) reported that daily exposures of mice to 75 mg/m^3 (15 ppm) of PAN 6 hr/day for 130 days caused a 30-percent weight loss compared to sham controls, 18 percent mortality, and pulmonary lesions. The most prevalent lesions were chronic hyperplastic bronchitis and proliferative peribronchiolitis.

Thomas et al. (1977) found that mice exposed to 22.3 mg/m^3 of PAN (4.5 ppm) for 2 hr and subsequently challenged with a Streptococcus sp. aerosol for 1 hr showed a significant increase in mortality and a reduction in mean survival rate, compared to mice exposed to air. No effect on the incidence of fatal pulmonary infection or survival time was observed in mice challenged with Streptococcus sp. 1 hr before the pollutant exposure (27.2 mg/m^3 of PAN for 3 hr). Thomas et al. (1981a) published additional data that extend observations of reduced resistance of mice to streptococcal pneumonia over a range of exposures to PAN. A single 2- or 3-hr exposure to PAN at 14.8 to 28.4 mg/m^3 (3.0 to 5.7 ppm) caused a significant increase in the susceptibility of mice to streptococcal pneumonia. The mean excess mortality rate ranged from 8 to 39 percent. Mice exposed to O_3 at 0.98 mg/m^3 (0.5 ppm) and challenged with the S. pyogenes aerosol resulted in a mean excess mortality (38 percent) that was almost equivalent to the excess mortality for the group exposed to 28.4 mg/m^3 of PAN. The results agreed with earlier reports that PAN is less toxic than O_3 to mice exposed under ambient conditions. Exposure to 7.4 mg/m^3 (1.5 ppm) of PAN 3 hr/day, 5 days/week for 2 weeks had no appreciable effect, although no statistics were provided. Neither exposure routine altered the morphology, viability, or phagocytic activity of isolated macrophages, although there was a decrease in ATP levels. The other noticeable effect was that macrophages isolated from the animals that were repeatedly exposed failed to attach themselves to a glass substrate. These investigators also studied whether a chronic infection initiated with an exposure to Mycobacterium tuberculosis (RIRv) was influenced by subsequent exposure to PAN. The exposure to this oxidant (25 mg/m^3 for 6 days) did not alter the pattern of bacterial growth in the lungs of mice.

10.5.2 Hydrogen Peroxide

Although concentrations of hydrogen peroxide (H_2O_2) as high as 0.14 mg/m^3 (0.10 ppm) have been reported to occur in urban air samples (Chapter 6), very little is known about the effects of H_2O_2 from inhalation exposure. Most of the early work on H_2O_2 toxicity involved exposure to very high concentrations. Oberst et al. (1954) investigated the inhalation toxicity of 90 percent H_2O_2 vapor in rats, dogs, and rabbits at concentrations ranging from 10 mg/m^3 (7 ppm) daily for six months to an 8-hr exposure to 338 mg/m^3 (243 ppm). After autopsy, all animals showed abnormalities of the lung. In a recent experiment, Last et al. (1982) exposed rats for 7 days to > 95-percent H_2O_2 gas with a concentration of 0.71 mg/m^3 (0.5 ppm) in the presence of respirable ammonium sulfate particles. No significant effects were observed in body weight, lung lobe weights, and protein or DNA content of lung homogenates. The authors suggested that because H_2O_2 is highly soluble, it is not expected to penetrate to the deep lung, which may account for the absence of observed effects.

The majority of studies on the H_2O_2 explore possible mechanisms for the effects of H_2O_2. These include direct cellular effects associated with in vitro exposure to H_2O_2 and biochemical reactions to H_2O_2 generated in vivo.

Hydrogen peroxide may affect lung function by the alteration of pulmonary surfactant. Wilkins and Fettissoff (1981) found that 10^{-2} to 10^{-1}M of H_2O_2 increased the surface tension of saline extracts of dog lung homogenates. The authors estimated that a dog breathing 1.4 mg/m^3 (1 ppm) of H_2O_2 for 30 hr would build up a pollutant concentration of 10^{-2}M in the surfactant, assuming that all the H_2O_2 was retained by the lungs. However, as stated above, this estimate of tissue dose is not realistic, because most of the H_2O_2 would be absorbed in the upper airway.

Another mechanism by which H_2O_2 may affect ventilation is by changing the tone of airway smooth muscle. Stewart et al. (1981) reported that 10^{-4}M of H_2O_2 caused significant constriction of strips of subpleural canine lung parenchyma and of bovine trachealis muscle. In the distal airway preparation (canine), this contraction was reversed by catalase. Pretreatment of both proximal (bovine) and distal muscle strips with meclofenamate or idomethacin markedly reduced the response to H_2O_2. This suggested that the increase in airway smooth muscle tone produced by H_2O_2 involves prostaglandin-like substances.

The potential genotoxic effects from in vitro H_2O_2 exposure have been evaluated in isolated cell systems. Bradley et al. (1979) reported that H_2O_2 produced both toxicity and single-strand DNA breaks but was not mutagenic at concentrations up to 530 μM. They observed a significant increase in the frequency of reciprocal sister chromatid exchanges in V-79 Chinese hamster cells at a concentration of 353 μM of H_2O_2. However, the authors pointed out that sister chromatid exchange frequency was not necessarily equivalent to increased mutant frequency. In subsequent experiments, Bradley and Erickson (1981) confirmed these observations in V-79 Chinese hamster lung cells and were unable to detect any DNA-protein or DNA-DNA crosslinks with 353 μM of H_2O_2 for 3 hr at 37°C. Increases in the frequency of sister chromatid exchanges in Chinese hamster cells have also been found by MacRae and Stich (1979), Speit and Vogel (1982), and Speit et al. (1982). Wilmer and Natarajan (1981) reported only a slight enhancement in the frequency of sister chromatid exchanges in Chinese hamster ovary cells following treatment with up to 10^{-3}M of H_2O_2. In comparison, cells were killed with a concentration of 10^{-1}M of H_2O_2. Similarly, H_2O_2 (10^{-1}mg/ml) was negative in the Ames mutagenicity assay (Ishidate and Yoshikawa, 1980), and several other investigators have confirmed the lack of mutagenicity for H_2O_2 (Stich et al., 1978; Kawachi et al., 1980).

Johnson et al. (1981) reported that the intrapulmonary instillation of glucose oxidase, a generator of H_2O_2, increases lung permeability in rats. A greater increase in lung permeability was achieved by the addition of a combination of glucose oxidase and lactoperoxidase than by the glucose oxidase-H_2O_2-generating system alone. Horseradish peroxidase did not effectively substitute for lactoperoxidase in the potentiation of damage. Injury was blocked by catalase but not by superoxide dismutase (SOD), suggesting that H_2O_2 or its metabolites, rather than superoxide, were involved. Because horseradish peroxidase did not potentiate the glucose oxidase damage, the authors speculated that the mechanism of injury occurs through the action of a halide-dependent pathway described for cell injury produced by H_2O_2 and lactoperoxidase/myeloperoxidase (MPO) (Klebanoff and Clark, 1975). Any source of H_2O_2 plus MPO and a halide cofactor is capable of catalyzing many oxidation and halogenation reactions (Clark and Klebanoff, 1975), but other possible mechanisms of oxygen radical production have been proposed (Halliwell, 1982).

Carp and Janoff (1980) have shown that a H_2O_2 generating system with MPO and Cl^- will suppress the elastase inhibitory capacity of the protease inhibitor (BMPL) present in bronchial mucus. This antiprotease is capable of inhibiting the potentially dangerous proteases found in human polymorphonuclear leukocytes (PMNs), including elastase and cathepsin-G. Inactivation of BMPL could make the respiratory mucosa more susceptible to attack by inflammatory cell proteases. Human PMN have not been shown to contain MPO but macrophages may contain analogous forms of peroxidase.

In other *in vitro* experiments, Suttorp and Simon (1982) demonstrated that H_2O_2 generated by glucose oxidase was cytotoxic to cultured lung epithelial cells (L_2 cells) in a concentration-dependent fashion. Cytotoxicity was measured by determining ^{51}Cr release from target cells. Cytotoxicity was prevented by the addition of catalase. It was stressed that there is no established identity between the L_2 cell line and the *in situ* type 2 pneumocytes from which they were derived.

10.5.3 Complex Pollutant Mixtures

Additional toxicological studies have been conducted on the potential action of complex mixtures of oxidants and other pollutants. Animals have been exposed under laboratory conditions to ambient air from high oxidant areas, to UV-irradiated and nonirradiated reaction mixtures of automobile exhaust and air, and to other combinations of interactive pollutants. Although these mixtures attempt to simulate the photochemical reactions produced under actual atmospheric conditions, they are extremely difficult to analyze because of their chemical complexity. Variable concentrations of total oxidants, carbon monoxide, hydrocarbons, nitrogen oxides, sulfur oxides, and other unidentified complex pollutants have been reported. For this reason, the studies presented in this section differ from the more simplified combinations of O_3 and one or two other nonreactive pollutants discussed under previous sections of the chapter. The effects described in animals exposed to UV-irradiated exhaust mixtures are not necessarily uniquely characteristic of O_3, but most of them could have been produced by O_3. In most cases, however, the biological effects presented would be difficult to associate with any one pollutant.

Research on ambient air and UV-irradiated or nonirradiated exhaust mixtures is summarized in Table 10-27. Long-term exposure of various species of animals to ambient California atmospheres have produced changes in the pulmonary function of guinea pigs (Swann and Balchum, 1966; Wayne and Chambers, 1968) and have produced a number of biochemical, pathological, and behavioral effects in mice, rats, and rabbits (Wayne and Chambers, 1968; Emik and Plata, 1969; Emik et al., 1971). Exposure to UV-irradiated automobile exhaust containing oxidant levels of 0.2 to 1.0 ppm produced histopathologic changes (Nakajima et al., 1972) and increased susceptibility to infection (Hueter et al., 1966) in mice. Both UV-irradiated and nonirradiated mixtures produced decreased spontaneous running activity (Hueter et al., 1966; Boche and Quilligan, 1960) and decreased infant survival rate and fertility (Kotin and Thomas, 1957; Hueter et al., 1966; Lewis, et al., 1967) in a number of experimental animals. Pulmonary changes were demonstrated in guinea pigs after short-term exposure to irradiated automobile exhaust (Murphy et al., 1963; Murphy, 1964) and in dogs after long-term exposure to both irradiated and nonirradiated automobile exhaust (Lewis et al., 1974; Orthoefer et al., 1976). Irradiation of the air-exhaust mixtures led to the formation of photochemical reaction

TABLE 10-27. EFFECTS OF COMPLEX POLLUTANT MIXTURES

Concentration,[a] (ppm)	Pollutant[b]	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
			A. Ambient air		
0.032 - 0.050 9.1 - 13.5 0.044 - 0.077 0.019 - 0.144	O_x CO NO_2 NO	Lifetime study, continuous	No clear chronic effects; "suggestive" changes in pulmonary function, morphology, and incidence of pulmonary adenomas in aged animals. Increased 17-ketosteroid excretion in guinea pigs. Decreased glutamic oxalacetic transaminase in blood serum of rabbits.	Mouse, rat, hamster, guinea pig, rabbit	Wayne and Chambers, 1968
0.057 1.7 2.4 0.019 0.015 0.004	O_x CO HC NO_2 NO PAN	2.5 years, continuous	Reduced pulmonary alkaline phosphatase (rats); reduced serum glutamic oxaloacetic transaminase (rabbits); increased pneumonitis (mice); increased mortality (male mice); reduced body weights (mice); decreased running activity (male mice); no significant induction of lung adenomas (mice).	Mouse, rat, rabbit	Emik et al., 1971
0.062 - 0.239 0.03 - 0.07 2.7 - 4.4	O_x NO_2 HC	13 months, continuous	Decreased spontaneous running activity.	Mouse	Emik and Plata, 1969.
0.27 - 0.31 13 - 38 2 - 9 0.09 - 0.70	O_x CO HC NO_x	1 year, continuous	Expiratory flow resistance increased on days when O_x reached $\geq$ 0.30 ppm or at combined concentrations of $\geq$ 40 ppm of CO, 16 ppm of HC, and 1.2 ppm of NO_x. Indidividual sensitivity demonstrated. Temperature was an important variable.	Guinea pig	Swann and Balchum, 1966
0.4 (max)	O_x	19 weeks, continuous	No consistent effects on conception rate, litter rate, or newborn survival.	Mouse	Kotin and Thomas, 1957

TABLE 10-27. EFFECTS OF COMPLEX POLLUTANT MIXTURES (continued)

Concentration,[a] (ppm)	Pollutant[b]	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
			B. Automobile exhaust		
0.012- 0.65 3.0 0.04 - 1.10 0.06 - 5.00 0.06 - 1.20	O_3 (max) HC (propylene) NO_2 NO SO_2	0.5-6 hr (diesel)	UV-irradiation of propylene, SO_2, NO, and NO_2 produced O_3 and a mutagenic moiety when collected particles were tested by the plate-incorporation test. Irradiation did not alter and O_3 tended to reduce the mutagenic response.	Salmonella typhimurium	Claxton and Barnes, 1981
0.04 - 0.2 0.15 - 0.5 0.4 - 1.8 6 - 36 20 - 100	O_3 NO_2 NO HC (CH_4)	1.5 - 23 mo	Increased pulmonary infection. Decreased fertility and infant survival. No significant changes in pulmonary function. Decreased spontaneous running activity during the first few weeks of exposure.	Mouse, rat, hamster, guinea pig	Hueter et al., 1966 Lewis et al., 1967
0.1 - 0.5 0.2 - 0.6 5 - 8 40 - 60	O_x NO_x HC CO	4 weeks, 5 days/week, 2-3 hr/day	Histopathologic changes resembling tracheitis and bronchial pneumonia at the higher concentration range of oxidants.	Mouse	Nakajima et al., 1972
0.2 - 0.4 100 24 - 30 0.1 - 1.0 0.1 - 2.0 0.42 - 0.49 0.02 - 0.03	O_3 CO HC (CH_4) NO_2 NO SO_2 H_2SO_4	18-68 months, 7 days/week, 16 hr/day	No cardiovascular effects	Dog	Bloch et al., 1972, 1973 Gillespie, 1980
		2-3 years recovery in ambient air.	No significant differences in collagen: protein ratios; prolyl hydroxylase increased with high concentrations of all mixes.	Dog	Orthoefer et al., 1976
			Pulmonary function for groups receiving oxidants [irradiated exhaust (I) $\pm$ SO_x] 18 months: no effects 36 months: no effects	Dog	Vaughan et al., 1969 Lewis et al., 1974

TABLE 10-27. EFFECTS OF COMPLEX POLLUTANT MIXTURES (continued)

Concentration,[a] (ppm)	Pollutant[b]	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
			61 months: N_2 washout increased (I); R_L increased (I, $I+SO_x$).	Dog	Lewis et al., 1974
			2 years recovery: P_aCO_2 increased ($I+SO_x$); V_D increased (I, $I+SO_x$); D_{Lco}/TLC decreased and V_c increased in all groups; lung compartment volumes increased ($I+SO_x$).	Dog	Gillespie, 1980
			Morphology (32-36 months recovery): air space enlargement; nonciliated bronchiolar hyperplasia; foci of ciliary loss with and without squamous metaplasia in trachea and bronchi.	Dog	Hyde et al., 1978
0.33 - 0.82 0.16 - 5.50 0.16 - 4.27 0.12 - 2.42 0.02 - 0.20	O_x NO_2 NO Formaldehyde Acrolein	4-6 hr	Increased pulmonary flow resistance, increased tidal volume, decreased breathing frequency due to formaldehyde and acrolein at low O_x: aldehyde ratio. Decreased tidal volume, increased frequency, increased pulmonary resistance due to O_x and NO_x at high O_x: aldehyde ratio.	Guinea pig	Murphy et al., 1963; Murphy, 1964
			C. Other complex mixtures		
0.08 0.76 2.05 1.71	O_3 SO_2 T-2 Butene acetaldehyde	4 weeks 7 days/week 23 hr/day	Alteration in distribution of ventilation (ΔN_2) and increased diffusing capacity.	Hamster	Raub et al., 1983b
0.3 1.0 2.0	O_3 NO_2 SO_2	2 weeks 7 days/week 23 hr/day	Voluntary activity (wheel running) decreased 75% after 1-3 days, returning to 85% of pre-exposure levels by the end of 14 days.	Mouse	Stinson and Loosli, 1979

TABLE 10-27. EFFECTS OF COMPLEX POLLUTANT MIXTURES (continued)

Concentration,[a] (ppm)	Pollutant[b]	Exposure duration and protocol	Observed effect(s)[c]	Species	Reference
0.40 - 0.52 1.0 - 2.15	O_3 O_x (gas vapor)	24 hr	Decreased spontaneous wheel running activity.	Mouse	Boche and Quilligan, 1960
1.25	Ox (gas vapor)	19 weeks, continuous	Decreased conception rate, litter rate, and newborn survival.	Mouse	Kotin and Thomas, 1957

[a] Ranked by nonspecific oxidant concentration (O_3 or O_x).

[b] Abbreviations used: O_3 = ozone; O_x = oxidant; CO = carbon monoxide; NO = nitrogen oxide, NO_2 = nitrogen dioxide; NO_x = nitrogen oxides; SO_2 = sulfur dioxide; HC = hydrocarbon; CH_4 = methane; H_2SO_4 = sulfuric acid; PAN = peroxyacetyl nitrate.

[c] See Glossary for the identification of pulmonary symbols.

products that were biologically more active than nonirradiated mixtures. The concentration of total oxidant as expressed by O_3 ranged from 588 to 1568 $\mu g/m^3$ (0.30 to 0.80 ppm) in the irradiated exhaust mixtures, compared to only a trace or no oxidant detected in the nonirradiated mixtures.

The description of effects following exposure of dogs for 68 months to automobile exhaust, simulated smog, oxides of nitrogen, oxides of sulfur, and their combination has been expanded in a monograph by Stara et al. (1980). The dogs were examined after 18 months (Vaughan et al., 1969), 36 months (Lewis et. al., 1974), 48 to 61 months (Bloch et al., 1972, 1973; Lewis et al., 1974), and 68 months (Orthoefer et al., 1976) of exposure; the dogs were examined again 24 months (Gillespie, 1980) or 32 to 36 months (Orthoefer et al., 1976; Hyde et al., 1978) after exposure ceased. Only those results pertaining to oxidant exposure are described in this section, which limits the discussion to groups exposed to irradiated automobile exhaust (I) and irradiated exhaust supplemented with sulfur oxides ($I+SO_x$). See Table 10-27 for exposure concentrations.

No specific cardiovascular effects were reported during the course of exposures (Bloch et al., 1971, 1972, 1973) or 3 years after exposure (Gillespie, 1980). Similarly, Orthoefer et al. (1976) reported no significant biochemical differences in the collagen to protein ratio in tissues of dogs exposed for 68 months or after 2.5 to 3 years of recovery in ambient air. However, prolyl hydroxylase levels were reported to have increased in the lungs of dogs exposed to I and $I+SO_x$, when compared to control air and the nonirradiated exhaust alone or in combination with SO_x.

No significant impairment of pulmonary function was found after 18 months (Vaughan et al., 1969) or 36 months (Lewis et al., (1974) of exposure. However, by 61 months of exposure, Lewis et al. (1974) reported increases in the nitrogen washout of dogs exposed to I, and higher total expiratory resistance in dogs exposed to both I and $I+SO_x$, when compared to their respective controls receiving clean air and SO_x alone. Two years after exposure ceased, pulmonary function was remeasured by Gillespie (1980). These measurements were made in a different laboratory than the one used during exposure, but consistency among measurements of the control group and another set of dogs of similar age at the new laboratory indicated that this difference did not have a major impact on the findings. Arterial partial pressure of CO_2 increased in the group exposed to $I+SO_x$ and total deadspace increased in the the I and $I+SO_x$

groups. The diffusing capacity for carbon monixide (D_{Lco}) was similar in all exposure groups, but when normalized for total lung capacity (TLC), the D_{Lco}/TLC ratio was smaller in exposed groups than in the air control group. Mean capillary blood volumes also increased in all exposed groups. No changes in lung volumes were reported at the end of exposure (Lewis et al., 1974). However, when lung volumes from these animals were measured 2 years later, increases were reported in the I+SO_x group. Unfortunately, the sample size of dogs exposed to I was too small (n = 5) to permit meaningful comparisons. In general, pulmonary function changes were found to be similar in all groups exposed to automobile exhaust alone or supplemented with SO_x. Exposure to these mixtures with or without UV-irradiation produced lung alterations normally associated with injury to the airway and parenchyma.

The functional abnormalities mentioned above showed relatively good correlation with structural changes reported by Hyde et al. (1978). After 32 to 36 months of recovery in clean air, morphologic examination of the lungs by light microscopy, scanning electron microscopy, and transmission electron microscopy revealed a number of exposure-related effects. The displaced volume of the fixed right lung was larger in the I-exposed group. Both the I and I+SO_x groups showed random enlargement of alveolar airspaces centered in respiratory bronchioles and alveolar ducts. Small hyperplastic lesions were observed at the junction of the terminal bronchiole and the first-order respiratory bronchiole. Foci of ciliary loss associated with squamous metaplasia were also observed in the intrapulmonary bronchi of the I+SO_x group. However, because these was no significant difference in the magnitude of these lesions, oxidant gases and SO_x did not appear to act in an additive or synergistic manner.

Additional work on irradiated and nonirradiated automobile exhaust has been presented by Claxton and Barnes (1981). The mutagenicity of diesel exhaust particle extracts collected under smog-chamber conditions was evaluated by the Salmonella typhimurium plate-incorporation test (Ames et al., 1975). The authors demonstrated that the irradiation of propylene, SO_2, NO, and NO_2 produced O_3 and a mutagenic moiety. In baseline studies on diesel exhaust, in which O_3 was neither added nor produced, the mutagenicity of each sample was similar under dark or UV-light conditions. When O_3 was introduced into the smog chamber, the mutagenicity of the organic compounds was reduced.

The behavioral effect of a nonirradiated reaction mixture was examined by Stinson and Loosli (1979). Voluntary wheel-running activity was recorded during a continuous 2-week exposure to synthetic smog containing 588 $\mu g/m^3$ (0.3 ppm) of O_3, 1 ppm of NO_2, and 2 ppm of SO_2, or to each component separately. An immediate decrease in spontaneous activity occurred after 1 to 3 days of exposure, returning to 85 percent of the original activity by the end of exposure. Activity returned to basal levels 5 days after breathing filtered air. Ozone alone produced a response that was similar to that of the synthetic smog mixture. Since NO_2 and SO_2 alone had only moderate effects, the authors concluded that O_3 had the major influence on depression of activity.

More recently, Raub et al. (1983b) reported pulmonary function changes in hamsters exposed 23 hr/day for 4 weeks to a nonirradiated reaction mixture of trans-2-butene, O_3, and SO_2. Decreases in the nitrogen washout slope and increases in the diffusing capacity indicated a significant compensatory change in distrubution of ventilation in the lungs of exposed animals. Animals compromised by the presence of emphysema were unable to respond to this pulmonary insult in the same manner as animals without impaired lung function.

10.6 SUMMARY

10.6.1 Introduction

The biological effects of O_3 have been studied extensively in animals and a wide array of toxic effects have been ascribed to O_3 inhalation. Although much has been accomplished to improve the existing data base, refine the concentration-response relationships and interpret better the mechanisms of O_3 effects, many of the present data were not accumulated with the idea that quantitative comparisons would be drawn. In many cases, only qualitative comparisons can be made. To maximize the extent that animal toxicological data can be used to estimate the human health risk of exposure to O_3, the qualitative as well as quantitative similarities between the toxicity of O_3 to animals and man must be considered in the future. Significant advances have been made in understanding the toxicity of O_3 through appropriate animal models. This summary highlights the significant results of selected studies that will provide useful data for better predicting and assessing, in a scientifically sound manner, the possible human responses to O_3.

10.6.2 Regional Dosimetry in the Respiratory Tract

Experiments on the nasopharyngeal removal of O_3 in animals demonstrate that the fraction of O_3 uptake depends inversely on flow rate and O_3 concentration, that uptake is greater for nose than for mouth breathing, and that tracheal and chamber concentrations are positively correlated. Only one experiment measured O_3 uptake in the lower respiratory tract, finding 80 to 87 percent uptake by the lower respiratory tract of dogs.

The model of Aharonson et al. (1974) is useful in analyzing nasopharyngeal uptake data. Applied to O_3 data, the model indicates that the average mass transfer coefficient in the nasopharyngeal region increases with increasing air flow. Application of the LaBell et al. (1955) model to nasopharyngeal uptake is inappropriate, because it does not include the effects of chemical reactions.

The McJilton model (McJilton et al., 1972) and the Miller model (Miller et al., 1978) for lower respiratory tract O_3 uptake are very similar in their treatment of O_3 in the airways (taking into account convection, diffusion, wall losses, and ventilatory patterns) and in their use of morphological data to define the dimensions of the airways and liquid lining. However, the Miller model is more realistic, because it accounts for chemical reactions of O_3 with constituents of the mucous-serous layer. Tissue dose is predicted by the Miller model to be relatively low in the trachea and to increase to a maximum around the junction of the conducting airways and the gas exchange region and then to decrease distally. Comparison of the Miller model results to the morphological effects of O_3 indicates qualitative agreement in the pulmonary region. However, comparison in the tracheobronchial region indicates further research is needed to define the relevant toxic, chemical, and physical mechanisms.

At present, there are few experimental results that are useful in judging the validity of the modeling efforts. Such results are needed, not only to understand better the absorption of O_3 and its role in toxicity, but also to support and to lend confidence to the modeling efforts. With experimental confirmation, models will become practical tools and further our understanding of the role of O_3 in the respiratory tract.

Ozone dosimetry modeling is in its initial stages; refinements and experimental information are needed. The models (nasopharyngeal and lower respiratory tract) raise many questions, not only about the model formulations and assumptions, but more importantly, they bring to the forefront questions about what is needed to understand the absorption of O_3 in the respiratory tract.

10.6.3 Effects of Ozone on the Respiratory Tract

10.6.3.1 Morphological Effects. Morphological studies of the effects of O_3 have indicated that the pattern and distribution of the tissue lesions are similar in the species studied and depend on the locations of the sensitive cells and the junction between the conducting airways and the gas exchange regions of the lung. Damage to all parts of the respiratory tract can occur in animals, depending on the O_3 concentration. At low concentrations of O_3 (< 1960 $\mu g/m^3$, 1 ppm) damage is principally confined to the junction between the alveoli and the conducting airways. Dogs, monkeys, and man have respiratory and nonrespiratory bronchioles, but the common experimental animals (mice, rats, rabbits, and guinea pigs) have only nonrespiratory bronchioles. The location of the O_3 lesion thus differs according to the species examined (Plopper et al., 1979; Castleman et al., 1977, 1980; Dungworth et al., 1975a; Eustis et al., 1981). In both types of lungs, the effects of O_3 have been found at concentrations as low as 392 $\mu g/m^3$ (0.2 ppm) and for exposure times as short as 2 hr (Stephens et al., 1974a).

In the upper and lower conducting airways, ciliated cells appear to be the most sensitive cell type; they are damaged by exposures as low as 392 to 1568 $\mu g/m^3$ (0.2 to 0.8 ppm) 8 or 24 hr for 7 days in rats (Schwartz et al., 1976), bonnet monkeys (Castleman et al., 1977), Rhesus monkeys (Dungworth et al., 1975b; Mellick et al., 1977), and mice (Ibrahim et al., 1980). When Moore and Schwartz (1981) and Boorman et al. (1980) extended these exposure levels to 180 days, similar changes in these ciliated cells were observed. Uniform damage is not always noted; most often reports are of shortened and less dense cilia occurring in random patches. Electron microscopy revealed severe cytoplasmic changes and condensed nuclei. Damage is present in both trachae and bronchi (Eustis et al., 1981; Mellick et al., 1977; Castleman et al., 1977). The damaged cilia are replaced by nonciliated clara cells that become hyperplasic (Evans et al., 1976a; Lum et al., 1978).

In mice, O_3 levels of 980 and 1568 $\mu g/m^3$ (0.5 and 0.8 ppm) elicited a pronounced hyperplasia of these nonciliated cells that persisted for 10 days after cessation of the exposure (Zitnik et al., 1978; Ibrahim et al., 1980). In a number of species, O_3 damage is clearly evident at the centriacinar region, which includes the terminal bronchiole region, portions of the respiratory bronchioles, and possibly the alveolar ducts, depending on the species (Stephens et al., 1973, 1974a,b; Schwartz et al., 1976; Mellick et al., 1977).

The type 1 epithelial cells are significantly affected (Stephens et al., 1974a; Evans et al., 1976a; Castleman et al., 1980; Eustis et al., 1981; Barry et al., 1983; Boorman et al., 1980). In monkeys, for example, at 1764 $\mu g/m^3$ (0.9 ppm) the type 1 cell death reaches a maximum at 12 hr after continuous exposure (Castleman et al., 1980). With the destruction of these cells, there is a hyperplasia of type 2 alveolar epithelial cells, which recovers the denuded basal lamina (Stephens et al., 1974a,b; Sherwin et al., 1983; Eustis et al., 1981). The type 2 cells are relatively resistant to O_3 exposure.

Following and during continued exposures, these type 2 cells begin to proliferate, which is a hallmark of O_3 injury regardless of species. In rats, DNA synthesis in type 2 cells was reported as early as 4 hr after exposure to 392 $\mu g/m^3$ (0.2 ppm) (Stephens et al., 1974a) and reached a maximum at 2 days following continuous exposure to 686 or 980 $\mu g/m^3$ (0.35 or 0.5 ppm) (Evans et al., 1976a,b), or 1568 $\mu g/m^3$ (0.8 ppm) (Boorman et al., 1980). Although type 2 cells proliferated in the O_3-exposed lung, complete maturation of type 2 cells to type 1 cells did not occur, even as late as 180 days of exposure (Moore and Schwartz, 1981). In the normal progression, type 2 cells would have matured into type 1 cells. Continued O_3 exposure inhibits both ciliagenesis and type 2 cell maturation.

Inflammation occurs in all species so far examined. The inflammatory response is seen as early as 4 hr after exposure to 1568 $\mu g/m^3$ (0.8 ppm) in monkeys (Castleman et al., 1980). In rats and monkeys, inflammation persists with continued exposure, although at reduced levels. The inflammatory exudate includes both fibrin and various leukocytes in the initial phase. In the later phase the inflammatory cells are predominantly macrophages (Castleman et al., 1980; Brummer et al., 1977; Boorman et al., 1980; Moore and Schwartz, 1981). Quantitative estimates of the degree of inflammation are, however, lacking at present. The contribution of the inflammatory response to subsequent long-term features of O_3 toxicity has not been studied in detail, even though techniques are available. A number of studies have reported that exposure to 980 $\mu g/m^3$ (0.5 ppm) and above thickens the interalveolar septa of centriacinar alveoli (Schwartz et al., 1976; Castleman et al., 1980; Boorman et al., 1980). Thickness could be due to interstitial fibrosis.

Although some delay has been observed between the exposure to O_3 and the maximum manifestation of morphological changes, the shortest time required for O_3 exposure to result in significant morphological changes is 2 hr of exposure to 392 or 980 $\mu g/m^3$ (0.2 or 0.5 ppm) in rats (Stephens et al., 1973, 1974a,b) or 4.7 or 6.6 hr of exposure by endotracheal tube in cats to 510, 980, or 1960 $\mu g/m^3$ (0.26, 0.5, or 1 ppm) (Boatman et al., 1974). However, most of these morphological studies were specifically designed to look at long-term (i.e., days, months, years) exposures rather than acute effects. These data based on acute studies are in agreement with molecular theories that ozone acts rapidly to oxidize some critical tissue component. Little difference in severity was noted by Schwartz et al. (1976) between exposure to 8 hr/day or 24 hr/day when the exposure was continued for 7 days. Quantitative studies of different exposure regimens are lacking, but technically feasible. The sequence in which the anatomic sites are affected appears to be a function of concentration rather than of exposure duration. Increasing concentrations not only results in more severe lesions, but also extends the lesion to higher generations of the respiratory structure.

Morphological studies of vitamin E-deficient or supplemented rats have been undertaken to correlate the biochemical findings with morphological alterations (Plopper et al., 1979; Stephens et al., 1983; Chow et al., 1981; Schwartz et al., 1976; Sato et al., 1976a,b, 1978, 1980). Despite the presence of vitamin E in the diets of these animals, the morphological lesion of O_3 exposure was unchanged.

When comparisons are made at the analogous anatomical site, the morphological effects of O_3 on the lungs of a number of species of animals are remarkably similar. Despite the inherent differences in anatomy between most experimental animals and man, the junction between the conducting airways and the gas exchange region is most affected by O_3.

10.6.3.2 Lung Function. Changes in lung function following O_3 exposure have been studied in mice, rats, guinea pigs, rabbits, cats, dogs, sheep, and monkeys. Short-term exposure for 2 hr to concentrations of 431 to 980 $\mu g/m^3$ (0.22 to 0.5 ppm) produces rapid, shallow breathing and increased pulmonary resistance measured during exposure (Murphy et al., 1964; Yokoyama, 1969; Watanabe et al., 1973; Amdur et al., 1978). The onset of these effects is rapid and the abnormal breathing pattern usually disappears within 30 min after cessation of exposure. Other changes in lung function measured following short-term O_3 exposures lasting 3 hr to 14 days are usually greatest

1 day following exposure and disappear by 7 to 14 days following exposure. These effects are associated with premature closure of the small, peripheral airways and include increased residual volume, closing volume, and closing capacity (Inoue et al., 1979).

Long-term exposure of 4 to 6 weeks to O_3 concentrations of 392 to 490 $\mu g/m^3$ (0.2 to 0.25 ppm) increases lung distensibility at high lung volumes in young rats (Bartlett et al., 1974; Raub et al., 1983a). Similar increases in lung distensibility were found in older rats exposed to 784 to 1568 $\mu g/m^3$ (0.4 to 0.8 ppm) for up to 180 days (Moore and Schwartz, 1981; Costa et al., 1983; Martin et al., 1983). Three to twelve months of exposure to O_3 concentrations of 1176 to 1568 $\mu g/m^3$ (0.6 to 0.8 ppm) increased pulmonary resistance and caused impaired stability of the small, peripheral airways in both rats and monkeys (Costa et al., 1983; Wegner, 1982). The effects in monkeys were not completely reversed by 3 months following exposure; lung distensibility had also decreased in the postexposure period, suggesting the development of lung fibrosis.

Studies of airway reactivity following O_3 exposure in experimental animals show that O_3 increases the reactivity of the lung to mechanical and chemical stimulation partly by increased sensory neural activity travelling in the vagus nerve and partly by a local action of O_3 on the tissues. Aerosolized ovalbumin can reach immunologic receptors in the lungs of mice exposed to 980 or 1568 $\mu g/m^3$ (0.5 or 0.8 ppm) continuously for 3 to 5 days (Osebold et al., 1980), resulting in an increased incidence of anaphylaxis. Increased sensitivity to histamine or cholinomimetic drugs by aerosol or injection has been noted in several species. Easton and Murphy (1967) showed that the lethal dose of histamine in guinea pigs was reduced in those animals exposed to concentrations as low as 980 or 1960 $\mu g/m^3$ (0.5 or 1 ppm) of O_3 for 2 hr. The pulmonary resistance due to subcutaneous injection of histamine increased in guinea pigs exposed to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 for 1 hr (Gordon and Amdur, 1980). Similarly, dogs exposed to 1372 and 1960 $\mu g/m^3$ (0.7 and 1.0 ppm) of O_3 for 2 hr had greater changes in pulmonary resistance following histamine aerosol inhalation (Lee et al., 1977; Holtzman et al., 1983a). Sheep exposed to 980 $\mu g/m^3$ (0.5 ppm) of O_3 for 2 hr experienced increased pulmonary resistance for the cholinomimetic drug, carbachol (Abraham et al., 1980). The time course of O_3-induced airway hyperreactivity suggests a possible association with inflammation (Holtzman et al., 1983a,b; Sielczak et al., 1983; Fabbri et al., 1984), but responses are variable and not very well understood.

Additional studies that demonstrate increased collateral resistance following 30-min local exposure of O_3 or histamine in sublobar bronchi of dogs (Gertner et al., 1983a,b,c) suggest that other mechanisms, along with amplification of reflex pathways, may contribute to changes in airway reactivity.

10.6.3.3 Biochemically Detected Effects of Ozone. Increased activity of the glutathione peroxidase system is one of the most sensitive indices of exposure to $\leq$ 1960 $\mu g/m^3$ (1 ppm) of O_3 measured biochemically. The increases in the glutathione peroxidase system are thought to be protective, because this system is involved in antioxidant metabolism. Concurrent increases in O_2 consumption of mitochondria are also observed. Mustafa (1975) and Mustafa et al. (1976, 1983) summarized a number of experiments with rats; they showed that continuous exposure between 392 and 1568 $\mu g/m^3$ (0.2 and 0.8 ppm) for 7 days caused a concentration-related increase in the activities of succinate oxidase, succinate-cytochrome c reductase, NADPH-cytochrome c reductase, lactate dehydrogenase, glucose-6-phosphate dehydrogenase, glutathione reductase, glutathione peroxidase, and the levels of reduced glutathione. Numerous investigators have also found similar increases when studying rats, mice, and monkeys (Chow, 1983; Plopper et al., 1979; Schwartz et al., 1976; Moore et al., 1980; Fukase et al., 1975; Chow et al., 1974, 1975; Mustafa et al., 1982). Increases in the glutathione peroxidase system have been reported after exposure of rats on a vitamin E-deficient diet to levels as low as 196 $\mu g/m^3$ (0.1 ppm) for 7 days (Chow et al., 1981; Mustafa, 1975; Mustafa and Lee, 1976). The dietary vitamin E fed to the rats influenced the increase of this system. For example, when the diet of rats had 66 ppm of vitamin E, increased activities were observed at 392 $\mu g/m^3$ (0.2 ppm) of O_3; with 11 ppm of vitamin E, increases occurred at 196 $\mu g/m^3$ (0.1 ppm) (Mustafa and Lee, 1976). Several other investigators have shown that vitamin E deficiency in rats makes them more susceptible to these enzymatic changes (Chow et al., 1981; Plopper et al., 1979; Chow and Tappel, 1972).

The influence of the pattern of exposure on these effects of O_3 on antioxidant metabolism and O_2 consumption have been investigated (DeLucia et al., 1975a,b; Fukase et al., 1975; Chow and Tappel, 1973; Mustafa and Lee, 1976). Generally, over a 7-day continuous exposure to about 1568 $\mu g/m^3$ (0.8 ppm) of O_3, there is a slight (usually nonsignificant) decrease in enzyme activities on day 1 of exposure. The activities then increase by day 2, plateau by about day 4, and are still elevated at day 7. When both continuous and intermittent (8 hr/day) exposure regimens are compared for several O_3 concentrations (392, 980, or 1568 $\mu g/m^3$; 0.2, 0.5 or 0.8 ppm), no differences between the regimens are observed in rats (Chow et al., 1974; Schwartz et al., 1976; Mustafa and Lee, 1976; DeLucia et al., 1975a).

Antioxidant metabolism and O_2 consumption have been examined in mice, rats, and monkeys after O_3 exposure. Generally, similar effects were noted, although different concentrations were required sometimes to elicit effects. For example, rats were affected by an 8-hr/day, 7-day exposure to 980 $\mu g/m^3$ (0.5 ppm) of O_3, but rhesus monkeys were not affected (Chow et al., 1975). Rhesus monkeys were affected after 7 days of intermittent exposure to 1568 $\mu g/m^3$ (0.8 ppm) (Mustafa and Lee, 1976). Rats and bonnet monkeys have been compared by Mustafa and Lee (1976). After 7 days of intermittent exposure to 980 $\mu g/m^3$ (0.5 ppm), the rats and monkeys had equivalent increases in succinate oxidase activity. Direct comparison of mice and rats shows that for several of the biochemical endpoints, the increases in mice were significantly greater than the increases in rats (Mustafa et al., 1982). Quantitative evaluation of species sensitivity from these studies is not possible. For example, in the rat and monkey studies, some O_3 concentrations were not equal, and statistical design and analyses were inadequate. In addition, differences in the deposition of O_3 between rats and monkeys is not known. Thus, it may only be generally stated that apparently rats were more responsive than monkeys.

Age-dependent responsiveness to O_3 has been described in rats exposed to 1568 or 1764 $\mu g/m^3$ (0.8 or 0.9 ppm) of O_3. Generally, the youngest rats (7 to 18 days old) exhibited decreases in enzyme activities; 20- to 24-day-old rats had marginal increases (if at all); adult, 35- to 90-day-old rats had an increase in enzyme activities (Tyson et al., 1982; Lunan et al., 1977; Elsayed et al., 1982a). The reasons for this age dependence are unknown. It might be due to a complex interrelationship between sensitivity (because basal levels of enzymes studied differed by age) and dosimetry of O_3.

The numerous studies of antioxidant metabolism and oxygen consumption are summarized in Table 10-5. A few mechanisms for the increases in these metabolic systems are possible: increased enzyme content within a given cell; same enzyme content, but an increase in the number of cells with such enzymes; or a combination of the two. The former potential mechanism has not been studied. Mustafa et al. (1973), Mustafa (1975), and DeLucia et al. (1975a) found that O_2 consumption of the whole lung increased, the number of mitochondria in the lung increased, and the specific enzyme activity of mitochondria (activity per milligram of mitochondrial protein, e.g., per mitochondrion) did not increase. Several investigators have found close correlations between the pattern of changes in these enzymes and increases in the number of type 2 cells, which have more mitochondria than type 1 cells, in the lung (Plopper et al., 1979; Chow et al., 1981; Schwartz et al., 1976; DeLucia et al., 1975a). Thus, the available experimental evidence suggests that the mechanism responsible for these enzymatic changes is the hyperplasia of type 2 cells after O_3 exposure. However, the presence of a concurrent increase in activities per cell that makes a small contribution to the overall response cannot be ruled out.

The activities of other enzymes increase in the lung following O_3 exposure. The total lactate dehydrogenase activity was increased in lungs of rats after exposure to 980 $\mu g/m^3$ (0.5 ppm) (Chow et al., 1977). Lysosomal enzymes were increased in lungs of rats (Dillard et al., 1972; Castleman et al., 1973a) and may reflect part of the inflammatory process (e.g., the influx of alveolar macrophages, which have high levels of these enzymes) seen throughout periods of O_3 exposure, as well as the breakdown of the exposed alveolar macrophages.

Decreases in the activities of several enzymes in the lung have also been reported. The cytochrome P-450 system has been studied because of its function in drug and carcinogen metabolism. Montgomery and Niewoehner (1979) reported a 50 percent decrease of benzphetamine N-demethylase activity, which is a cytochrome P-450-dependent enzyme, in the rat following a 24-hr exposure to 1960 $\mu g/m^3$ (1 ppm). In other studies, a decrease in the activity of benzpyrene hydroxylase in lung parenchyma of hamsters and in tracheobronchial mucosae of the rabbit was observed at 1470 $\mu g/m^3$ (0.75 ppm) (Palmer et al., 1971, 1972). Acute exposure of rabbits to 1960 $\mu g/m^3$ (1.0 ppm) also decreased levels of lung micrososomal cytochrome P-450 (Goldstein, 1975).

Collagen, a major structural protein of the lungs, is also altered by O_3 exposure. Typically, the activities of prolyl hydroxylase (the rate-limiting enzyme for the formation of hydroxyproline) and hydroxyproline (a major constituent of collagen) are measured. Last et al. (1979) observed a linear relationship between the increase in collagen synthesis and O_3 concentrations between 980 and 3920 $\mu g/m^3$ (0.5 and 2 ppm). If exposure was prolonged, hydroxyproline decreased by 180 days of exposure to 980 $\mu g/m^3$ (0.5 ppm) (Last and Greenberg, 1980). Recovery from increases in collagen metabolism are not immediate. After a 7-day exposure of rats to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 ceased, about 10 days were required for recovery of prolyl hydroxylase activity; hydroxyproline levels remained increased 28 days postexposure (Hussain, 1976a). The minimal exposure regimen causing an increase in prolyl hydroxylase activity in rats is a 7-day continuous exposure to 980 $\mu g/m^3$ (0.5 ppm); 392 $\mu g/m^3$ (0.2 ppm) caused no effects (Hussain et al., 1976a,b). The increased collagen synthesis has been correlated with fibrosis detected histologically in the same experiment (Last et al., 1979; Moore and Schwartz, 1981). Bhatnagar et al. (1983) found that collagen synthesis also increases in mice exposed to 882 $\mu g/m^3$ (0.45 ppm) of O_3. Thus, the response is not species-specific.

Although several investigators have found that in vitro exposure to O_3 affects lipids, very few in vivo studies have been conducted. Continuous exposure to 980 $\mu g/m^3$ (0.5 ppm) for 2, 4, or 6 weeks alters fatty acid composition of the lungs in rats, and acute (4 hr) exposure to a higher level (1960 $\mu g/m^3$; 1 ppm) decreases incorporation of fatty acids into lecithin in rabbits (Roehm et al., 1972; Kyei-Aboagye et al., 1973).

Ozone exposure (1176 to 4116 $\mu g/m^3$; 0.6 to 2.1 ppm) inhibits the phenol red activity transport mechanism from the lung to the circulation in a concentration-related manner (Williams et al., 1980). The noncarrier-mediated diffusion of phenol red from the lung increased simutaneously with the inhibition of the carrier-mediated transport. An increase in lung permeability, as evident by the diffusion of plasma proteins into the airways following O_3 exposure, has been reported in dogs (Reasor et al., 1979), rats (Alpert et al., 1971a), and guinea pigs (Hu et al., 1982). The protein content of lung lavage fluid from vitamin C-deficient guinea pigs was not different from those receiving adequate vitamin C. The influx of protein was proportional to the O_3 concentration to which the guinea pigs had been exposed in the concentration range of 510 to 1470 $\mu g/m^3$ (0.26 to 0.75 ppm) for 3 hr (Hu et al., 1982).

It is generally agreed that the toxic effects of O_3 can be ascribed to its oxidative capacity. As a powerful oxidant, O_3 can react with virtually every class of biological substance; this makes identification of the critical or essential toxic lesion almost impossible.

Two general hypotheses have been put forth to explain the toxic effects of O_3 on a molecular basis. The first hypothesis is that the oxidation of thiols or amino acids in tissue proteins or small molecular weight peptides is responsible (Mudd and Freeman, 1977). The second is that the oxidation of polyunsaturated fatty acids (PUFA) to fatty acid peroxides (FAP) results in toxicity (Menzel, 1970). A careful study of the biochemical, physiological, and morphological effects of O_3 exposure points to the cellular membranes as the site of toxicity. Both mechanisms could occur at the membrane. Because membranes are composed of both proteins and lipids, damage to one is difficult to separate from damage to the other or to both. Because the metabolism of FAP is linked to the glutathione peroxidase system (Chow and Tappel, 1972), depletion of thiols such as glutathione (GSH) by O_3 could enhance the toxicity of FAPs. The two theories are thus not separate, but complementary, and most likely oxidation of both PUFAs and proteins occurs simultaneously.

Although O_3 is a general reactant, the relative rates of reaction with different biological substances is remarkably different. Ozone oxidizes ethylene groups 1000 times faster than other compounds. Consequently, attention has been focused on PUFAs as targets for O_3 reaction. The Criegee mechanism for addition of O_3 across unsaturations is still a popular hypothesis. In the presence of protonic solvents such as water, peroxides can result directly from the decomposition of the initial O_3 adduct. Pryor et al. (1983) have also suggested that free radicals are generated directly by other mechanisms during the ozonation of PUFAs. Regardless of the chemical mechanism, once free radicals are generated in membranes, the toxic effects are similar. These effects are a loss of regulation of electrolytes and water (changes in permeability), leakage of essential intracellular enzymes from the cell, and inhibition of metabolic chains imbedded in mitochondrial or microsomal matricies (Menzel, 1976). If damage is sufficiently severe, the cell cannot recover and dies. Necrosis is commonly reported in the lungs of animals exposed to high concentrations of O_3.

Perhaps the most compelling evidence for PUFA peroxidation _in vivo_ is the protective effect of dietary vitamin E on O_3 toxicity (Roehm et al., 1971a,b and 1972; Chow and Tappel, 1972; Fletcher and Tappel, 1973; Donovan et al., 1977; Sato et al., 1976a,b; Chow and Kaneko, 1979; Plopper et al., 1979; Chow et al., 1981; Chow, 1983; Mustafa et al., 1982). Vitamin E as a phenolic antioxidant easily inhibits the peroxidation of PUFAs initiated _in vitro_ by O_3 (Roehm et al., 1971a). Indirect evidence that vitamin E protects against O_3-initiated peroxidation of PUFAs _in vivo_ is presented by the studies of Dumelin et al. (1978b), who found that the exhaled ethane and pentane in the breath of rats was decreased when vitamin E was provided in their diets.

Ethane and pentane are thought to be produced by peroxidation of PUFAs initiated by O_3 inhalation. Changes in lung fatty acid composition due to peroxidation are not easily interpreted because of the complexity of lung PUFA composition and difficulties in quantitative analysis. Direct evidence of peroxidation of PUFAs in human subjects has, however, been lacking.

Amino acids are oxidized by O_3 (Mudd et al., 1969; Mudd and Freeman, 1977; Previero et al., 1964). Cysteine, methionine and tryptophan are the three most easily oxidized amino acids. Human alpha-1-protease inhibitor is destroyed by ozonolysis *in vitro*, presumably by oxidation of methionine, tyrosine and tryptophan amino acid residues in the molecule (Johnson, 1980). The activity of a large number of enzymes is decreased immediately after O_3 exposure to 1960 to 7840 $\mu g/m^3$ (1 to 4 ppm) for 1 hr or more (DeLucia et al., 1972; Mountain, 1963; Kyei-Aboagye et al., 1973; Holzman et al., 1968; Goldstein et al., 1975; Menzel et al., 1976). Lung mitochondria lose their respiratory control following O_3 exposure (Mustafa et al., 1973). DeLucia et al. (1975b) also reported the depletion of GSH and the formation of mixed disulfides in the lungs of O_3-exposed rats.

In contrast to the decrease in enzyme activity by acute, high-level O_3 exposure, the glutathione peroxidase system consisting of glucose-6-phosphate dehydrogenase, glutathione reductase and glutathione peroxidase is increased in the lungs of rats exposed repeatedly to lower levels of O_3 ($\leq$ 1960 $\mu g/m^3$, 1 ppm) (Chow et al., 1981, 1974; Chow and Tappel, 1972, 1973; Mustafa and Lee, 1976; Moore et al., 1980). These effects would favor the concept that O_3 increases PUFA peroxidation, which induces the glutathione peroxidase system as a protective mechanism. Thus, with the available data, it would appear that both direct oxidation of low-molecular-weight compounds and proteins, as well as lipid peroxidation, can occur with O_3 exposure.

10.6.3.4 Host Defense Mechanisms. To protect man and other mammals from inhaled infectious agents, the mammalian lung possesses an array of defense mechanisms. Considerable effort has been expended in studies of the effects of O_3 on such defense mechanisms in hopes of understanding the underlying mechanisms and predicting concentration-response relationships.

Inhaled viable microorganisms as well as airborne particles are removed from the lung by two mechanisms. Ciliated cells of the respiratory tract propel mucus carrying entrapped particles and infectious agents upwards from the distal regions of the lung to be swallowed and excreted. Alveolar macrophages engulf, kill, and remove infectious agents from the respiratory regions of the lung either by migrating with the microbe to the mucus lining to be propelled upwards or to the lymphatic system to be drained from the lung.

Ciliated cells are damaged by O_3 inhalation, as demonstrated by major morphological changes in these cells including necrosis and sloughing or by the shortening of the cilia in cells attached to the bronchi. Ciliated cell damage should result in decreased transport of viable and non-viable particles from the lung. Rats exposed to 784, 1568, or 2352 $\mu g/m^3$ (0.4, 0.8, or 1.2 ppm) for times as short as 4 hr have decreased short-term clearance of particles from the lung (Phalen et al., 1980; Frager et al., 1979; Kenoyer et al., 1981). Short-term clearance is mostly due to mucus removal of particles, and the decreased short-term clearance is an anticipated functional result predicted from morphological observations. The mucous glycoprotein production of the trachea is also altered by O_3 exposure, but not in a simple manner. Mucous glycoprotein biosynthesis, as measured *ex vivo* in cultured tracheal explants from exposed rats, was inhibited by short-term continuous exposure to 1568 $\mu g/m^3$ (0.8 ppm) of O_3 for 3 to 5 days (Last and Cross, 1978; Last and Kaizu, 1980; Last et al., 1977). Glycoprotein synthesis and secretion recovered to control values after 5 to 10 days of exposure and increased to greater than control values after 10 days of exposure.

The long-term clearance of particles from the lung is a function of the alveolar macrophages (AM), which are damaged by O_3 inhalation. Most studies have been with rabbits, in which a 3-hr exposure to 980 $\mu g/m^3$ (0.5 ppm) reduces phagocytosis (Coffin and Gardner, 1972b; Coffin et al., 1968b), disrupts AM membranes (Dowell et al., 1970; Goldstein et al., 1977; Hadley et al., 1977), reduces AM lysosomal hydrolyase activity (Hurst et al., 1970, 1971), prevents AM migration (Schwartz and Christman, 1979; McAllen et al., 1981), and reduces AM numbers (Coffin et al., 1968b; Alpert et al., 1971b). The bactericidal capacity of AMs is also impaired; this has been attributed to the inhibition of superoxide anion radical production capacity by O_3 exposure (Witz et al., 1982; Amoruso et al., 1981; Goldstein et al., 1971a,b, 1972; Warshauer et al., 1974; Bergers et al., 1982).

An integrated measure of both of these mechanisms of viable organism removal and the more general measures of host defense against airborne infections can be determined by the airborne infection of animals following O_3

exposure. This method, known as the infectivity model, has recently been described in detail by Gardner (1982a). A number of different animals and bacterial infectious agents have been used to illustrate the increased susceptibility of animals to airborne infections following very modest concentrations and times of exposure. To date, it is one of the most sensitive measures of ozone toxicity. Mice exposed to 157 to 196 µg/m^3 (0.08 to 0.1 ppm) for 3 hr are significantly more susceptible to bacterial infection than mice exposed to clean air (Coffin et al., 1968a; Ehrlich et al., 1977; Miller et al., 1978). This increase in susceptibility was also evident after an intermittent exposure to 196 µg/m^3 (0.1 ppm) for 103 days (Aranyi et al., 1983). Adding SO_2 and $(NH_4)_2$ SO_4 to O_3 did not further enhance the mortality rate. However, combining O_3 with either NO_2 or H_2SO_4 had an additive effect in this infectivity system (Gardner et al., 1977; Grose et al., 1982; Ehrlich et al., 1977; Ehrlich et al., 1979; Ehrlich, 1980). The effects of O_3 were more pronounced when the test animals exercised during O_3 exposure (Illing et al., 1980.) Such a study demonstrates that the activity level of the test subject is an important variable that can influence the host response.

Immunological effects of O_3 have only been scantily studied in mice and guinea pigs. Depression of the cell-mediated immune response has been measured at high O_3 concentrations (2901 µg/m^3, 1.48 ppm) in the guinea pig (Thomas et al., 1981b). The systemic immune response is depressed in mice, as measured by the blastogenic response of splenic lymphocytes to the T-cell mitogens PHA and Con-A (Aranyi et al., 1983). Mice were exposed to 196 µg/m^3 (0.1 ppm) 5 hr/day, 5 days/week for 90 days.

10.6.3.5 Tolerance. Examination of responses to short-term, repeated exposures to O_3 clearly indicates that with some of the parameters measured, animals have an increased capacity to resist the effects of subsequent exposure. This tolerance persists for varying times, depending on the degree of development of the tolerance. Previous low levels of exposure to O_3 will certainly protect against subsequent lethal doses and the development of edema (Stokinger et al., 1956; Fairchild, 1967; Coffin and Gardner, 1972a). The delay in mucociliary activity (i.e., clearance reported for O_3) can also be eliminated by preexposure to a lower concentration. This effect is only for a short period of time and is lost as soon as the mucus secretion rate returns to normal. However, not all of the toxic effects of O_3, such as reduced functioning activity of the pulmonary defense system (Gardner et al., 1972); hyperplasia of the type 2 cells (Evans et al., 1971, 1976a,b); increased susceptibility to respiratory disease (Gardner and Graham, 1977); loss of pulmonary enzymatic activity (Chow, 1976, Chow et al., 1976b); and inflammatory response (Gardner et al., 1972) can be prevented by prior treatment with low levels of O_3. Dungworth et al. (1975b) and Castleman et al. (1980) have attempted to explain tolerance by careful examination of the morphological changes that occur with repeated O_3 exposures. These investigators suggest that during continuous exposure to O_3 the injured cells attempt to initiate early repair of the specific lesion. This repair thus results in a reduction of the effect first observed. At this time, there are a number of hypotheses proposed to explain the mechanism of this phenomenon (Mustafa and Tierney, 1978; Schwartz et al., 1976; Mustafa et al., 1977; Berliner et al., 1978; Gertner et al., 1983b; Bhatnagar et al., 1983). From this literature, it would appear that tolerance, as seen in animals, may not be the result of any one single biological process, but instead may result from a number of different routes, depending on the specific response measured. Tolerance does not imply complete or absolute protection, because continuing injury does still occur, which could potentially lead to nonreversible pulmonary changes.

10.6.4 Extrapulmonary Effects

It was formerly believed that O_3, on contact with respiratory system tissue, immediately reacted and thus was not absorbed or transported to extrapulmonary sites. However, several studies suggest that either O_3 or products formed by the interaction of O_3 and respiratory system tissue produce effects in lymphocytes, erythrocytes, and serum, as well as in the parathyroid gland, the myocardium, the liver, and the CNS. Ozone exposure also produces effects on animal behavior that may be caused by pulmonary consequences of O_3, or by nonpulmonary (CNS) mechanisms. The mechanism by which O_3 causes extrapulmonary changes is unknown. Mathematical models of O_3 dosimetry predict that very little O_3 penetrates to the blood of the alveolar capillaries. Whether these effects result from O_3 or a reaction product of O_3 which penetrates to the blood and is transported is the subject of speculation.

10.6.4.1 Central Nervous System and Behavioral Effects. Ozone significantly affects the behavior of rats during exposure to concentrations as low as 235 $\mu g/m^3$ (0.12 ppm) for 6 hr. With increasing concentrations of O_3, further decreases in unspecified motor activity and in operant learned behaviors have been observed (Konigsberg and Bachman, 1970; Tepper et al., 1982; Murphy et al., 1964; and Weiss et al., 1981). Tolerance to the observed decrease in motor activity may occur on repeated exposure. At low O_3 exposure concentrations (490 $\mu g/m^3$, 0.25 ppm) an increase in activity is observed after exposure ends. Higher O_3 concentrations (980 $\mu g/m^3$, 0.5 ppm) produce a decrease in rodent activity that persists for several hours after the end of exposure (Tepper et al., 1982, 1983).

The mechanism by which behavioral performance is reduced is unknown. Physically active responses appear to enhance the effects of O_3, although this may be the result of an enhanced minute volume that increases the effective concentration delivered to the lung. Several reports indicate that it is unlikely that animals have reduced physiological capacity to respond, prompting Weiss et al. (1981) to suggest that O_3 impairs the inclination to respond. Two studies indicate that mice will respond to remove themselves from an atmosphere containing greater than 980 $\mu g/m^3$ (0.5 ppm) (Peterson and Andrews, 1963, Tepper et al., 1983). These studies suggest that the aversive effects of O_3 may be due to lung irritation. It is unknown whether lung irritation, odor, or a direct effect on the CNS causes change in rodent behavior at lower O_3 concentrations.

10.6.4.2 Cardiovascular Effects. Studies on the effects of O_3 on the cardiovascular system are few, and to date there are no reports of attempts to confirm these studies. Structural changes in the cell membranes and nuclei of the myocardium muscle fibers in mice were found after 3 weeks of exposure to 392 $\mu g/m^3$ (0.2 ppm) (Brinkman et al., 1964), and these effects were reversible in clean air. The exposure of rats to O_3 alone or in combination with cadmium (1176 $\mu g/m^3$, 0.6 ppm O_3) resulted in measurable increases in systolic pressure and heart rate (Revis et al., 1981). No additive or antagonistic response was observed with the combined exposure. Pulmonary capillary blood flow and PaO_2 decreased 30 min following exposure of dogs to 588 $\mu g/m^3$ (0.3 ppm) of O_3 (Friedman et al., 1983). The decrease in pulmonary capillary blood flow persisted for as long as 24 hr following exposure.

10.6.4.3 Hematological and Serum Chemistry Effects. The data base for the effects of O_3 on the hematological system is extensive and indicates that O_3 or one of its reactive products can cross the blood-gas barrier, causing changes in the circulating erythrocytes (RBC) as well as significant differences in various components of the serum.

Effects of O_3 on the circulating RBCs can be readily identified by examining either morphological and/or biochemical endpoints. These cells are structurally and metabolically well understood and are available through relatively non-invasive methods, which makes them ideal candidates for both human and animal studies. A wide range of structural effects have been reported in a variety of species of animals, including an increase in the fragility of RBCs isolated from monkeys exposed to 1470 $\mu g/m^3$ (0.75 ppm) of O_3 4 hr/day for 4 days (Clark et al., 1978). A single 4-hr exposure to 392 $\mu g/m^3$ (0.2 ppm) also caused increased fragility as well as sphering of RBCs of rabbits (Brinkman et al., 1964). An increase in the number of RBCs with Heinz bodies was detected following a 4-hr exposure to 1666 $\mu g/m^3$ (0.85 ppm). The presence of such inclusion bodies in RBCs is an indication of oxidant stress (Menzel et al., 1975a).

These morphological changes are frequently accompanied by a wide range of biochemical effects. RBCs of monkeys exposed to 1470 $\mu g/m^3$ (0.75 ppm) of O_3 for 4 days also had a decreased level of glutathione (GSH) and decreased acetylcholinesterase (AChE) activity, an enzyme bound to the RBC membranes. The RBC GSH activity remained significantly lower 4 days postexposure (Clark et al., 1978).

Animals deficient in vitamin E are uniquely sensitive to O_3. The RBCs from these animals, after being exposed to O_3, had a significant increase in the activity of GSH peroxidase, pyruvate kinase, and lactic dehydrogenase, but had a decrease in RBC GSH after exposure to 1568 $\mu g/m^3$ (0.8 ppm) for 7 days (Chow and Kaneko, 1979). Animals with a vitamin E-supplemented diet did not have any changes in glucose-6-phosphate dehydrogenase (G-6-PD), superoxide dismutase, or catalase activities. At a lower level (980 $\mu g/m^3$, 0.5 ppm), there were no changes in GSH level or in the activities of GSH peroxidase or GSH reductase (Chow et al., 1975). Menzel et al. (1972) also reported a significant increase in lysis of RBCs from vitamin E-deficient animals after 23 days of exposure to 980 $\mu g/m^3$ (0.5 ppm). These effects were not observed in vitamin E-supplemented rats. Mice on a vitamin E-supplemented diet and those on a deficient diet showed an increase in G-6-PD activity after an exposure of 627 $\mu g/m^3$ (0.32 ppm) of O_3 for 6 hr. Decreases observed in AChE activity occurred in both groups (Moore et al., 1980).

Other blood changes are attributed to O_3. Rabbits exposed for 1 hr to 392 $\mu g/m^3$ (0.2 ppm) of O_3 showed a significant drop in total blood serotonin (Veninga, 1967). Six- and 10-month exposures of rabbits to 784 $\mu g/m^3$ (0.4 ppm) of O_3 produced an increase in serum protein esterase and in serum trypsin inhibitor. This latter effect may be a result of thickening of the small pulmonary arteries. The same exposure caused a significant decrease in albumin levels and an increase in alpha and gamma globulins (P'an and Jegier, 1971, 1976; P'an et al., 1972; and Jegier, 1973). Chow et al. (1974) reported that the serum lysozyme level of rats increased significantly after 3 days of continuous exposure to O_3 but was not affected when the exposure was intermittent (8 hr/day, 7 days). The O_3 concentration in both studies was 1568 $\mu g/m^3$ (0.8 ppm) of O_3.

Short-term exposure to low concentrations of O_3 induced an immediate change in the serum creatine phosphokinase level in mice. In this study, the O_3 doses were expressed as the product of concentration and time. The C x T value for this effect ranged from 0.4 to 4.0 (Veninga et al., 1981).

A few of the hematological effects observed in animals (i.e., decrease in GSH and AChE activity and the formation of Heinz bodies) following exposure to O_3 have also been seen following in vitro exposure of RBCs from humans (Freeman and Mudd, 1981; Menzel et al., 1975b; Verweij and Van Steveninck, 1981). A common effect observed by a number of investigators is that O_3 inhibits the membrane ATPase activity of RBCs (Koontz and Heath, 1979; Kesner et al., 1979; Kindya and Chan, 1976; Freeman et al., 1979; Verweij and Van Steveninck, 1980). It has been postulated that this inhibition of ATPase could be related to the sphercytosis and increased fragility of RBCs seen in animal and human cells.

Although these in vitro data are useful in studying mechanisms of action, it is difficult to extrapolate these data to any effects observed in man. Not only is the method of exposure not physiological, but the actual concentration of O_3 reaching the RBC cannot be determined with any accuracy.

10.6.4.4 Reproductive and Teratogenic Effects. Pregnant animals may be at greater risk to the effects of O_3 because the volume of air inspired generally increases up to 50 percent during pregnancy. Experiments with mice suggest that perinatal exposure to 392 $\mu g/m^3$ (0.2 ppm) of O_3 can reduce infant survival (Brinkman et al., 1964) and increase the incidence of unlimited incisor growth in neonates (Veninga, 1967). Pregnant rats exposed to 2920 $\mu g/m^3$ (1.49 ppm) of O_3 during mid-gestation had a significantly higher embryo resorption rate than control rats (Kavlock et al., 1979). Progeny of dams exposed to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 during late gestation showed significantly slower neonatal growth rates, retarded early reflex development, and delayed onset of grooming and rearing behavior (Kavlock et al., 1980).

10.6.4.5 Chromosomal and Mutational Effects. That O_3 may have the potential for producing genotoxic effects has been postulated because of its radiomimetic properties. The decomposition of O_3 in water produces OH and HO_2 radicals, and it is these species that are considered to be the most biologically active products of ionizing radiation. Cytogenetic toxicity has been reported both in cells in culture and in cells isolated from animals exposure to O_3. A large portion of this data base, however, has been derived from studies conducted at extremely high levels of O_3, and because of this, these data will not be discussed further in this summary. The most relevant data concerning genotoxicity of O_3 are obtained from investigations in which the O_3 concentration did not exceed 1,960 $\mu g/m^3$ (1.0 ppm).

Zelac et al. (1971a,b) reported a significant increase in chromosome aberrations in peripheral blood lymphocytes in Chinese hamsters exposed to 392 $\mu g/m^3$ (0.2 ppm) for 5 hr. It was also reported that O_3 was additive with radiation. Tice et al. (1978) attempted to repeat the Zelac studies; however, a number of significant differences existed between these two studies that make direct comparison of the data difficult. Tice et al. did not find any increase in sister chromatid exchange or any increase in number of chromosome aberrations of phytohemagglutinin-stimulated peripheral blood, but they did find an increase in the number of chromatid deletions and achromatic lesions. Although both studies reported significant increases in chromosome aberrations in peripheral blood lymphocytes, the specific type of lesions reported were clearly different. Section 10.4.5 gives a detailed discussion of the importance of these differences. Gooch et al. (1976) analyzed the bone marrow samples from Chinese hamsters exposed to 451 $\mu g/m^3$ (0.23 ppm) of O_3 for 5 hr and the leukocytes and spermatocytes from mice exposed for up to 2 weeks to 412 $\mu g/m^3$ (0.21 ppm) of O_3. No effect was found on either the frequency of chromatid or chromosome aberrations, nor were there any reciprocal translocations in the primary spermatocytes. Guerrero et al. (1979) reported a concentration-related increase in the sister chromatid exchange in human fetal lung cells (WI-38) exposed *in vitro* to concentrations ranging from 490 to 1960 $\mu g/m^3$ (0.25 to 1.0 ppm) for 1 hr.

In summary, O_3 has been shown to produce a wide range of toxic effects on cells and on cellular components, including genetic material. Cytogenetic toxicity has been reported in cells in culture and in cells isolated from animals if O_3 exposure has occurred at sufficiently high levels and for sufficient long periods. The mutagenic effects of O_3 have been examined in only a very few instances, and unfortunately none of these investigations have used mammalian cells. The mutagenic properties of O_3 have been demonstrated in procaryotic and eucaryotic cells; however, the concentrations used were many orders of magnitude higher than what is found in the ambient environment.

10.6.4.6 Other Extrapulmonary Effects. A series of studies was conducted to show that O_3 increases drug-induced sleeping time in a number of species of animals (Gardner et al., 1974; Graham, 1979; Graham et al., 1981, 1982a,b, 1983a,b). At 1960 $\mu g/m^3$ (1.0 ppm), effects were observed after 1, 2, and 3 days of exposure. As the concentration of O_3 was reduced, increasing numbers of daily 3-hr exposures were required to produce a significant effect. At the lowest concentration studied (196 $\mu g/m^3$, 0.1 ppm), the increase was observed at days 15 and 16 of exposure. It appears that this effect is not specific to the strain of mouse or to the three species of animals tested, but it is sex-specific, with females being more susceptible. Recovery was complete within 24 hr after exposure. Although a number of mechanistic studies have been conducted, the reason for this effect on pentobarbital-induced sleeping time is not known. It has been hypothesized that some common aspect related to liver drug metabolism is quantitatively reduced (Graham et al., 1983a).

Several investigators have attempted to elucidate the involvement of the endocrine system in O_3 toxicity. Most of these studies were designed to investigate the hypothesis that the survival rate of mice and rats exposed to lethal concentrations of O_3 could be increased by use of various thyroid blocking agents or by thyroidectomy. To follow up these findings, Clemons and Garcia (1980a,b) investigated the effects of a 24-hr exposure to 1960 $\mu g/m^3$ (1.0 ppm) of O_3 on the hypothalamo-pituitary-thyroid system of rats. These three organs regulate the function of each other through various hormonal feedback mechanisms. Ozone caused decreases in serum concentration of thyroid stimulating hormone (TSH), in circulating thyroid hormones (T_3 and T_4) and in protein-bound iodine. No alterations were observed in many other hormone levels measured. Thyroidectomy prevented the effect of O_3 on TSH. The thyroid gland itself was altered (e.g., edema) by O_3. The authors interpreted these findings as an O_3-induced lowering of the hypothalamic set point for the pituitary-thyroid axis and a simultaneous reduction of the activity of prolactin inhibiting factor in the hypothalamus. The anterior pituitaries had fewer cells but more TSH per cell. These cells also released a greater amount of TSH into the culture medium.

By using LM and TEM, Atwal et al. (1975), Atwal and Wilson (1974), and Atwal and Pemsingh (1981) described changes in parathyroid glands in dogs and rabbits following short-term (up to 48 hr) exposure to 0.75 ppm of O_3. Changes identified include parenchymal atrophy, congestion, abundant secretory granules, leukocyte infiltration, and focal hemorrhages.

10.6.5 Effects of Other Photochemical Oxidants

There have been far too few controlled toxicological studies with the other oxidants to permit any sound scientific evaluation of their contribution to the toxic action of photochemical oxidant mixtures. The few toxicological studies on PAN indicate that it is much less acutely toxic than O_3. When the effects seen after exposure to O_3 and PAN are examined and compared, it is obvious that the test animals must be exposed to concentrations of PAN much greater than those needed with O_3 to produce a similar effect on lethality, behavior modification, morphology, or significant alterations in host pulmonary defense system (Campbell et al., 1967; Dungworth et al., 1969; Thomas et al., 1977, 1981a). The concentrations of PAN required to produce these effects are many times greater than what has been measured in the atmosphere (0.037 ppm).

Similarly, most of the investigations reporting H_2O_2 toxicity have involved concentrations much higher than those found in the ambient air (0.1 ppm), or the investigations were conducted by using various in vitro techniques for exposure. Very limited information is available on the health significance of inhalation exposure to gaseous H_2O_2. Because H_2O_2 is highly soluble, it is generally assumed that it does not penetrate into the alveolar regions of the lung but is instead deposited on the surface of the upper airways (Last et al., 1982). Unfortunately, there have not been studies designed to look for possible effects in this region of the respiratory tract.

A few in vitro studies have reported cytotoxic, genotoxic, and biochemical effects of H_2O_2 when using isolated cells or organs (Stewart et al., 1981; Bradley et al., 1979; Bradley and Erickson, 1981; Speit et al., 1982; MacRae and Stich, 1979). Although these studies can provide useful data for studying possible mechanisms of action, it is not yet possible to extrapolate these responses to those that might occur in the mammalian system.

Field and epidemiological studies have shown that human health effects from exposure to ambient mixtures of oxidants and other airborne pollutants can produce adverse human health effects (Chapter 12). Few such studies have been conducted with laboratory animals, because testing and measuring of such mixtures is not only complicated, but extremely costly. In these studies, the investigators attempted to simulate the photochemical reaction products produced under natural conditions and to define the cause-effect relationship.

Exposure to complex mixtures of oxidants plus the various components found in UV-irradiated auto exhaust indicates that certain effects, such as histopathological changes, increase in susceptibility to infection, a variety of altered pulmonary functional activities were observed in this oxidant atmosphere which was not reported in the nonirradiated exhaust (Murphy et al., 1963; Murphy, 1964; Nakajima et al., 1972; Hueter et al., 1966). Certain other biological responses were observed in both treatment groups, including a decrease in spontaneous activity, a decrease in infant survival rate, fertility, and certain pulmonary functional abnormalities (Hueter et al., 1966; Boche and Quilligan, 1960; Lewis et al., 1967).

Dogs exposed to UV-irradiated auto exhaust containing oxidants either with or without SO_x showed significant pulmonary functional abnormalities that had relatively good correlation with structural changes (Hyde et al., 1978; Gillespie, 1980; Lewis et al., 1974). There were no significant differences in the magnitude of the response in these two treatment groups, indicating that oxidant gases and SO_x did not interact in any synergistic or additive manner.

10.7 REFERENCES

Abraham, W. M.; Januszkiewicz, A. J.; Mingle, M.; Welker, M.; Wanner, A.; Sackner, M. A. (1980) Sensitivity of bronchoprovocation and tracheal mucous velocity in detecting airway responses to O_3. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 48: 789-793.

Abraham, W. M.; Lauredo, I.; Sielczak, M.; Yerger, L.; King, M. M.; Ratzan, K. (1982) Enhancement of bacterial pneumonia in sheep by ozone exposure. Am. Rev. Respir. Dis. Suppl. 125(4 pt. 2): 148.

Aharonson, E. F.; Menkes, H.; Gurtner, G.; Swift, D. L.; Proctor, D. F. (1974) Effect of respiratory airflow rate on removal of soluble vapors by the nose. J. Appl. Physiol. 27: 654-657.

Allman, P.; Dittmer, D. S. (1971) Lung volumes and other ventilatory variables during pregnancy: man. In: Respiration and Circulation. Bethesda, MD: Federation of American Societies for Experimental Biology; pp. 61-63.

Alpert, S. M.; Lewis, T. R. (1971) Ozone tolerance studies utilizing unilateral lung exposure. J. Appl. Physiol. 31: 243-246.

Alpert, S. M.; Schwartz, B. B.; Lee, S. D.; Lewis, T. R. (1971a) Alveolar protein accumulation. A sensitive indicator of low level oxidant toxicity. Arch. Intern. Med. 128: 69-73.

Alpert, S. M.; Gardner, D. E.; Hurst, D. J.; Lewis, T. R.; Coffin, D. L. (1971b) Effects of exposure to ozone on defensive mechanisms of the lung. J. Appl. Physiol. 31: 247-252.

Amdur, M. O.; Schultz, R. Z.; Drinker, P. (1952) Toxicity of sulfuric acid mist to guinea pigs. Arch. Ind. Hyg. Occup. Med. 5: 318-329.

Amdur, M. O.; Ugro, V.; Underhill, D. W. (1978) Respiratory response of guinea pigs to ozone alone and with sulfur dioxide. Am. Ind. Hyg. Assoc. J. 39: 958-961.

American Thoracic Society. (1962) Chronic bronchitis, asthma, and pulmonary emphysema. Am. Rev. Respir. Dis. 85: 762-768.

Ames, B. N.; McCann, J.; Yamasaki, E. (1975) Methods for detecting carcinogens and mutagens with the Salmonella/mammalian-microsome mutagenicity test. Mutat. Res. 31: 347-364.

Amoruso, M. A.; Witz, G.; Goldstein, B. D. (1981) Decreased superoxide anion radical production by rat alveolar macrophages following inhalation of ozone or nitrogen dioxide. Life Sci. 28: 2215-2221.

Aranyi, C.; Fenters, J.; Ehrlich, R.; Gardner, D. E. (1976) Scanning electron microscopy of alveolar macrophages after exposure to oxygen, nitrogen dioxide and ozone. EHP Environ. Health Perspect. 16: 180.

Aranyi, C., Vana, S. C.; Thomas, P. T.; Bradof, J. N.; Fenters, J. D.; Graham, J. A.; Miller, F. J. (1983) Effects of subchronic exposure to a mixture of O_3, SO_2 and $(NH_4)_2SO_4$ on host defenses of mice. J. Toxicol. Environ. Health 12: 55-71.

Astarita, G. (1967) Mass transfer with chemical reaction. New York, NY: Elsevier Publishing Co.; p. 187.

Atwal, O. S.; Pemsingh, R. S. (1981) Morphology of microvascular changes and endothelial regeneration in experimental ozone-induced parathyroiditis. Am. J. Pathol. 102: 297-307.

Atwal, O. S.; Wilson, T. (1974) Parathyroid gland changes following ozone inhalation. A morphologic study. Arch. Environ. Health 28: 91-100.

Atwal, O. S.; Samagh, B. S.; Bhatnagar, M. K. (1975) A possible autoimmune parathyroiditis following ozone inhalation. II. A histopathologic, ultrastructural, and immunofluorescent study. Am. J. Pathol. 80: 53-68.

Barry, B. E.; Miller, F. J.; Crapo, J. D. (1983). Alveolar epithelial injury caused by inhalation of 0.25 ppm of ozone. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc; pp. 299-309. (Advances in modern environmental toxicology: v. 5.)

Bartlett, D.; Faulkner, C. S. II; Cook, K. (1974) Effect of chronic ozone exposure on lung elasticity in young rats. J. Appl. Physiol. 37: 92-96.

Bergers, W. W. A.; Gerbrandy, J. L. F.; Stap, J. G.; Dura, E. A. (1983) Influence of air polluting components viz. ozone and the open air factor on host-resistance towards respiratory infections. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 459-467. (Advances in modern environmental toxicology: vol. 5).

Berliner, J. A.; Kuda, A.; Mustafa, M. G.; Tierney, D. F. (1978) Pulmonary morphologic studies of ozone tolerance in the rat (a possible mechanism for tolerance). Scanning Electron Microsc. 2: 879-884.

Bhatnagar, R. S.; Hussain, M. Z.; Sorensen, K. R.; Mustafa, M. G.; von Dohlen, F. M.; Lee, S. D. (1983) Effect of ozone on lung collagen biosynthesis. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, N.C. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 311-321. (Advances in modern environmental toxicology: vol. 5).

Bils, R. F. (1970) Ultrastructural alterations of alveolar tissue of mice. III. Ozone. Arch. Environ. Health 20: 468-480.

Bloch, W. N., Jr.; Miller, F. J.; Lewis, T. R. (1971) Pulmonary hypertension in dogs exposed to ozone. Cincinnati, OH: U.S. Environmental Protection Agency, Air Pollution Control Office.

Bloch, W. N., Jr.; Lassiter, S.; Stara, J. F.; Lewis, T. R. (1973) Blood rheology of dogs chronically exposed to air pollutants. Toxicol. Appl. Pharmacol. 25: 576-581.

Bloch, W. N., Jr.; Lewis, T. R.; Busch, K. A.; Orthoefer, J. G.; Stara, J. F. (1972) Cardiovascular status of female beagles exposed to air pollutants. Arch. Environ. Health 24: 342-353.

Boatman, E. S.; Sato, S.; Frank, R. (1974) Acute effects of ozone on cat lungs. II. Structural. Am. Rev. Respir. Dis. 110: 157-169.

Boatman, E. S.; Ward, G.; Martin, C. J. (1983) Morphometric changes in rabbit lungs before and after pneumonectomy and exposure to ozone. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 54: 778-784.

Boche, R. D.; Quilligan, J. J., Jr. (1960) Effects of synthetic smog on spontaneous activity of mice. Science (Washington, DC) 131: 1733-1734.

Boorman, G. A.; Schwartz, L. W.; Dungworth, D. L. (1980) Pulmonary effects of prolonged ozone insult in rats. Morphometric evaluation of the central acinus. Lab. Invest. 43: 108-115.

Boorman, G. A.; Schwartz, L. W.; McQuillen, N. K.; Brummer, M. E. (1977) Pulmonary response following long-term intermittent exposure to ozone: structural and morphological changes. Am. Rev. Respir. Dis. 115: 201.

Boushey, H. A.; Holtzman, M. J.; Sheller, J. R.; Nadel, J. A. (1980) State of the art: bronchial hyperreactivity. Am. Rev. Respir. Dis. 121: 389-413.

Bowes, C.; Cumming, G.; Horsfield, K.; Loughhead, J.; Preston, S. (1982) Gas mixing in an asymmetrical model of the pulmonary acinus and asymmetrical alveolar ducts. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 52: 221-225.

Bradley, M. O.; Erickson, L. C. (1981) Comparison of the effects of hydrogen peroxide and x-ray irradiation on toxicity, mutation, and DNA damage/repair in mammalian cells (V-79). Biochim. Biophys. Acta 654: 135-141.

Bradley, M. O.; Hsu, I.C.; Harris, C.C. (1979) Relationships between sister chromatid exchange and mutagenicity, toxicity, and DNA damage. Nature (London) 282: 318-320.

Brain J. D. (1980) Macrophage damage in relation to the pathogenesis of lung diseases. EHP Environ. Health Perspect. 35: 21-28.

Brain, J. D.; Sorokin, S. P.; Godleski, J. J. (1977) Quantification, origin, and fate of pulmonary macrophages. In: Brain, J. D.; Proctor, D. F.; Reid, C. M., eds. Respiratory Defense Mechanisms. New York, NY: Marcel Dekker, Inc.; pp. 849-891.

Brain, J. D.; Golde, D. W.; Green, G. M.; Massaro, D. J., Valberg, P. A.; Ward, P. A.; Werb, Z. (1978) Biological potential of pulmonary macrophages. Am. Rev. Respir. Dis. 118: 435-443.

Brinkman, R.; Lamberts, H.; Veninga, T. (1964) Radiomimetic toxicity of ozonized air. Lancet 1: 133-136.

Brummer, M. E. G.; Schwartz, L. W.; McQuillen, N. K. (1977) A quantitative study of lung damage by scanning electron microscopy. Inflammatory cell response to high-ambient levels of ozone. Scanning Electron Microsc. 2: 513-518.

Byers, D. H.; Saltzman, B. E. (1959) Determination of ozone in air by neutral and alkaline iodide procedures. In: Ozone chemistry and technology: Proceedings of the first international ozone conference; November, 1956; Chicago, IL. Washington, DC: American Chemical Society; pp. 93-101. (Advances in chemistry series: V. 21).

Calabrese, E. J.; Moore, G. S. (1980) Does the rodent model adequately predict the effects of ozone-induced changes to human erythrocytes? Med. Hypotheses 6: 505-507.

Calabrese, E. J.; Moore, G. S.; Greenwald, E. L. (1983a) Ozone-induced decrease of erythrocyte survival in adult rabbits. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 103-117. (Advances in modern environmental toxicology: vol. 5).

Calabrese, E. J.; Moore, G. S.; Williams, P. S. (1982) Effect of methyl oleate ozonide, a possible ozone intermediate, on normal and G-6-PD deficient erythrocytes. Bull. Environ. Contam. Toxicol. 29: 498-504.

Calabrese, E. J.; Moore, G. S.; Williams, P. S. (1983b) An evaluation of the Dorset sheep as a predictive animal model for the response of G-6-PD deficient human erythrocytes to a proposed systemic toxic ozone intermediate, methyl oleate hydroperoxide. Vet. Hum. Toxicol. 25: 241-246.

Calabrese, E. J.; Moore, G. S.; Weeks, B. L.; Stoddard, A. (1983c) The effect of ozone exposure upon hepatic and serum ascorbic acid levels in male Sprague-Dawley rats. J. Environ. Sci. Health A18: 79-93.

Campbell, K. I.; Hilsenroth, R. H. (1976) Impaired resistance to toxin in toxoid-immunized mice exposed to ozone on nitrogen dioxide. Clin. Toxicol. 9: 943-954.

Campbell, K. I.; Clarke, G. L.; Emik, L. O.; Plata, R. L. (1967) The atmospheric contaminant peroxyacetyl nitrate. Arch. Environ. Health 15: 739-744.

Campbell, K. I.; Emik, L. O.; Clarke, G. L.; Plata, R. L. (1970) Inhalation toxicity of peroxyacetyl nitrate: depression of voluntary activity in mice. Arch. Environ. Health 29: 22-27.

Carp, H.; Janoff, A. (1980) Inactivation of bronchial mucous proteinase inhibitor by cigarette smoke and phagocyte-derived oxidants. Exp. Lung Res. 1: 225-237.

Case, G. D.; Dixon, J. S.; Schooley, J. C. (1979) Interactions of blood metalloproteins with nitrogen oxides and oxidant air pollutants. Environ. Res. 20: 43-65.

Castleman, W. L.; Dungworth, D. L.; Tyler, W. S. (1973a) Cytochemically detected alterations of lung acid phosphatase reactivity following ozone exposure. Lab. Invest. 29: 310-319.

Castleman, W. L.; Dungworth, D. L.; Tyler, W. S. (1973b) Histochemically detected enzymatic alterations in rat lung exposed to ozone. Exp. Mol. Pathol. 19: 402-421.

Castleman, W. L.; Dungworth, D. L.; Tyler, W. S. (1975) Intrapulmonary airway morphology in three species of monkeys: A correlated scanning and transmission electron microscopic study. Am. J. Anat. 142: 107-121.

Castleman, W. L.; Tyler, W. S.; Dungworth, D. L. (1977) Lesions in respiratory bronchioles and conducting airways of monkeys exposed to ambient levels of ozone. Exp. Mol. Pathol. 26: 384-400.

Castleman, W. L.; Dungworth, D. L.; Schwartz, L. W.; Tyler, W. S. (1980) Acute respiratory bronchiolitis: an ultrastructural and autoradiographic study of epithelial cell injury and renewal in rhesus monkeys exposed to ozone. Am. J. Pathol. 98: 811-840.

Cavender, F. L.; Singh, B.; Cockrell, B. Y. (1978) Effects in rats and guinea pigs of six-month exposures to sulfuric acid mist, ozone and their combination. J. Toxicol. Environ. Health 4: 845-852.

Cavender, F. L.; Steinhagen, W. H.; Ulrich, C. E.; Busey, W. M.; Cockrell, B. Y.; Haseman, J. K.; Hogan, M. D.; Drew, R. T. (1977) Effects in rats and guinea pigs of short-term exposures to sulfuric acid mist, ozone, and their combination. J. Toxicol. Environ. Health 3: 521-533.

Chan, P. C.; Kinaya, R. J.; Kesner, L. (1977) Studies on the mechanism of ozone inactivation of erythrocyte membrane (Na^++K^+)-activated ATPase. J. Biol. Chem. 252: 8537-8541.

Chaney, S.; DeWitt, P.; Blomquist, W.; Muller, K.; Bruce, R.; Goldstein, G. (1979) Biochemical changes in humans upon exposure to ozone and exercise. Research Triangle Park, NC: U.S. Environmental Protection Agency, Health Effects Research Laboratory; EPA report no. EPA-600/1-79-026. Available from: NTIS, Springfield, VA; PB80-105554.

Chaney, S. G. (1981) Effects of ozone on leukocyte DNA. Research Triangle Park, NC: U.S. Environmental Protection Agency, Health Effects Research Laboratory; EPA report no. EPA-600/1-81-031. Available from: NTIS, Springfield, VA; PB81-179277.

Chang, H-K; Farhi, L. (1973) On mathematical analysis of gas transport in the lung. Respir. Physiol. 18: 370-385.

Chiappino, G.; Vigliani, E. C. (1982) Role of infective, immunological, and chronic irritative factors in the development of silicosis. Br. J. Ind. Med. 39: 253-258.

Chow, C. K. (1976) Biochemical responses in lungs of ozone-tolerant rats. Nature (London) 260: 721-722.

Chow, C. K. (1983) Influence of dietary vitamin E on susceptibility to ozone exposure. In: Lee, S. D., Mustafa, M. G; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc; pp. 75-93. (Advances in modern environmental toxicology: v. 5).

Chow, C. K.; Kaneko, J. J. (1979) Influence of dietary vitamin E on the red cells of ozone-exposed rats. Environ. Res. 19: 49-55.

Chow, C. K.; Tappel, A. L. (1972) An enzymatic protective mechanism against lipid peroxidation damage to lungs of ozone-exposed rats. Lipids 7: 518-524.

Chow, C. K.; Tappel, A. L. (1973) Activities of pentose shunt and glycolytic enzymes in lungs of ozone-exposed rats. Arch. Environ. Health 26: 205-208.

Chow, C. K.; Cross, C. E.; Kaneko, J. J. (1977) Lactate dehydrogenase activity and isoenzyme pattern in lungs, erythrocytes, and plasma of ozone-exposed rats and monkeys. J. Toxicol. Environ. Health 3: 877-884.

Chow, C. K.; Dillard, C. J.; Tappel, A. L. (1974) Glutathione peroxidase system and lysozyme in rats exposed to ozone or nitrogen dioxide. Environ. Res. 7: 311-319.

Chow, C. K.; Plopper, C. G.; Dungworth, D. L. (1979) Influence of dietary vitamin E on the lungs of ozone-exposed rats: a correlated biochemical and histological study. Environ. Res. 20: 309-317.

Chow, C. K.; Mustafa, M. G.; Cross, C. E.; Tarkington, B. K. (1975) Effects of ozone exposure on the lungs and the erythrocytes of rats and monkeys: relative biochemical changes. Environ. Physiol. Biochem. 5: 142-146.

Chow, C. K.; Plopper, C. G.; Chiu, M.; Dungworth, D. L. (1981) Dietary vitamin E and pulmonary biochemical and morphological alterations of rats exposed to 0.1 ppm ozone. Environ. Res. 24: 315-324.

Chow, C. K.; Aufderheide, W. M.; Kaneko, J. J.; Cross, C. E.; Larkin, E. C. (1976a) Effect of dietary vitamin E on the red blood cells of ozone-exposed rats. Fed. Proc. Fed. Am. Soc. Exp. Biol. 35: 741.

Chow, C. K.; Hussain, M. Z.; Cross, C. E.; Dungworth, D. L.; Mustafa, M. G. (1976b) Effect of low levels of ozone on rat lungs. I. Biochemical responses during recovery and reexposure. Exp. Mol. Pathol. 25: 182-188.

Christensen, E.; Giese, A. C. (1954) Changes in absorption spectra of nucleic acids and their derivatives following exposure to ozone and ultraviolet radiation. Arch. Biochem. Biophys. 51: 208-216.

Christman, C. A.; Schwartz, L. W. (1982) Enhanced phagocytosis by alveolar macrophages induced by short-term ozone insult. Environ. Res. 28: 241-250.

Clark, R. A.; Klebanoff, S. J. (1975) Neutrophil-mediated tumor cell cytotoxicity: role of the peroxidase system. J. Exp. Med. 141: 1442-1447.

Clark, K. W.; Posin, C. I.; Buckley, R. D.. (1978) Biochemical response of squirrel monkeys to ozone. J. Toxicol. Environ. Health 4: 741-753.

Claxton, L. D.; Barnes, H. M. (1981) The mutagenicity of diesel-exhaust particle extracts collected under smog-chamber conditions using the Salmonella typhimurium test system. Mutat. Res. 88: 255-272.

Clement, J.; Afschrift, M.; Pardens, J.; Van de Woestline, K. (1973) Peak expiratory flow rate and rate of change of pleural pressure. Respir. Physiol. 18: 222.

Clemons, G. K.; Garcia, J. F. (1980a) Endocrine aspects of ozone exposure in rats. Arch. Toxicol. Suppl. (4): 301-304.

Clemons, G. K.; Garcia, J. F. (1980b) Changes in thyroid function after short-term ozone exposure in rats. J. Environ. Pathol. Toxicol. 4: 359-369.

Coffin, D. L.; Blommer, E. J. (1970) Alteration of the pathogenic role of streptococci group C in mice conferred by previous exposure to ozone. In: Silver, I. H., ed. Aerobiology: proceedings of the third international symposium; September 1969; Sussex, England. New York, NY: Academic Press, Inc.; pp. 54-61.

Coffin, D. L.; Gardner, D. E. (1972a) The role of tolerance in protection of the lung against secondary insults. In: MEDICHEM: first international symposium of occupational physicians of the chemical industry; April; Ludwigshafen, West Germany. Ludwigshafen, West Germany: Badische Anilin-und Soda-Fabrik (BASF); pp. 344-364.

Coffin, D. L.; Gardner, D. E. (1972b) Interaction of biological agents and chemical air pollutants. Ann. Occup. Hyg. 15: 219-235.

Coffin, D. L.; Blommer, E. J.; Gardner, D. E.; Holzman, R. (1967) Effect of air pollution on alteration of susceptibility to pulmonary infections. In: Proceedings of the third annual conference on atmospheric contamination in confined spaces; May; Dayton, OH. Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratories; pp. 71-80; AMRL-TR-67-200.

Coffin, D. L.; Gardner, D. E.; Holzman, R. S.; Wolock, F. J. (1968) Influence of ozone on pulmonary cells. Arch. Environ. Health 16: 633-636.

Cosio, M. G.; Hale, K. A.; Niewoehner, D. E. (1980) Morphologic and morphometric effects of prolonged cigarette smoking on the small airways. Am. Rev. Respir. Dis. 122: 265-71.

Costa, D. L.; Kutzman, R. S.; Lehmann, J. R.; Popenoe, E. A.; Drew, R. T. (1983) A subchronic multi-dose ozone study in rats. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 369-393. (Advances in modern environmental toxicology: v. 5).

Cross, C. E.; DeLucia, A. J.; Reddy, A. K.; Hussain, M. Z.; Chow, C. K.; Mustafa, M. G. (1976) Ozone interactions with lung tissue: biochemical approaches. Am. J. Med. 60: 929-935.

DeLucia, A. J.; Hogue, P. M.; Mustafa, M. G.; Cross, C. E. (1972) Ozone interaction with rodent lung, effect on sulfhydryls and sulfhydryl-containing enzyme activities. J. Lab. Clin. Med. 80: 559-566.

DeLucia, A. J.; Mustafa, M. G.; Cross, C. E.; Plopper, C. G.; Dungworth, D. L.; Tyler, W. S. (1975a) Biochemical and morphological alterations in the lung following ozone exposure. In: Rai, C.; Spielman, L. A., eds. Air: I. pollution control and clean energy; 1973; New Orleans, LA; Detroit, MI; Philadelphia, PA; Vancouver, British Columbia. New York, NY: American Institute of Chemical Engineers; pp. 93-100. (AIChE symposium series: no. 147, v. 71).

DeLucia, A. J.; Mustafa, M. G.; Hussain, M. Z.; Cross, C. E. (1975b) Ozone interaction with rodent lung. III. Oxidation of reduced glutathione and formation of mixed disulfides between protein and nonprotein sulfhydryls. J. Clin. Invest. 55: 794-802.

Dillard, C. J.; Urribarri, N.; Reddy, K.; Fletcher, B.; Taylor, S.; de Lumen, B.; Langberg, S.; Tappel, A. L. (1972) Increased lysosomal enzymes in lungs of ozone-exposed rats. Arch. Environ. Health 25: 426-431.

Dixon, J. R.; Mountain, J. T. (1965) Role of histamine and related substances in development of tolerance to edemagenic gases. Toxicol. Appl. Pharmacol. 7: 756-766.

Donovan, D. H.; Menzel, D. B. (1975) Dietary and environmental modification of mouse lung lipids. American Oil Chemists' Society (Abstract).

Donovan, D. H.; Menzel, D. B. (1978) Mechanisms of lipid peroxidation: iron catalyzed decomposition of fatty acid hydroperoxides as the basis of hydrocarbon evolution in vivo. Experientia 34: 775-776.

Donovan, D. H.; Williams, S. J.; Charles, J. M.; Menzel, D. B. (1977) Ozone toxicity: Effect of dietary vitamin E and polyunsaturated fatty acids. Toxicol. Lett. 1: 135-139.

Dorsey, A. P.; Morgan, D. L.; Menzel, D. B. (1983) Filterability of erythrocytes from ozone-exposed mice. In: Abstracts of the third international congress on toxicology; September; San Diego, CA. Toxicol. Lett. 18(suppl. 1): 146.

Doty, R. L. (1975) Determination of odor preferences in rodents; methodological review. In: Moulton, D.G.; Turk, A.; Johnson, J.W., eds. Methods in olfactory research. New York, NY: Academic Press; pp. 395-406.

Dowell, A. R.; Lohrbauer, L. A.; Hurst, D.; Lee, S. D. (1970) Rabbit alveolar macrophage damage caused by in vivo ozone inhalation. Arch. Environ. Health 21: 121-127.

Downey, J. E.; Irving, D. H.; Tappel, A. L. (1978) Effects of dietary antioxidants on in vivo lipid peroxidation in the rat as measured by pentane production. Lipids 13: 403-407.

Dubeau, H.; Chung, Y. S. (1979) Ozone response in wild type and radiation-sensitive mutants of Saccharomyces cerevisiae. Mol. Gen. Genet. 176: 393-398.

Dubeau, H.; Chung, Y. S. (1982) Genetic effects of ozone induction of point mutations and genetic recombination in Saccharomyces cerevisiae. Mutat. Res. 102: 249-259.

Dumelin, E. E.; Dillard, C. J.; Tappel, A. L. (1978a) Breath ethane and pentane as measures of vitamin E protection of Macaca radiata against 90 days of exposure to ozone. Environ. Res. 15: 38-43.

Dumelin, E. E.; Dillard, C. J.; Tappel, A. L. (1978b) Effect of vitamin E and ozone on pentane and ethane expired by rats. Arch. Environ. Health 33: 129-134.

Dungworth, D. L. (1976) Short-term effects of ozone on lungs of rats, mice and monkeys. EHP Environ. Health Perspect. 16: 179.

Dungworth, D. L.; Clarke, G. L.; Plata, R. L. (1969) Pulmonary lesions produced in A-strain mice by exposure to peroxyacetylnitrates. Am. Rev. Respir. Dis. 99: 565-574.

Dungworth, D. L.; Cross, C. E.; Gillespie, J. R.; Plopper, C. G. (1975a) The effects of ozone on animals. In: Murphy, J. S.; Orr, J. R., eds. Ozone chemistry and technology. A review of the literature: 1961-1974. Philadelphia, PA: The Franklin Institute Press; pp. 29-54.

Dungworth, D. L.; Castleman, W. L.; Chow, C. K.; Mellick, P. W.; Mustafa, M. G.; Tarkington, B.; Tyler, W. S. (1975b) Effects of ambient levels of ozone on monkeys. Fed. Proc. Fed. Am. Soc. Exp. Biol. 34: 1670-1674.

Easton, R. E.; Murphy, S. D. (1967) Experimental ozone preexposure and histamine. Arch. Env. Health 15: 160-166.

Eglite, M. E. (1968) A contribution to the hygienic assessment of atmospheric ozone. Hyg. Sanit. 33: 18-23.

Ehrlich, R. (1963) Effect of air pollutants on respiratory infection. Arch. Environ. Health 6: 638-642.

Ehrlich, R. (1980) Interaction between environmental pollutants and respiratory infections. EHP Environ. Health Perspect. 35: 89-100.

Ehrlich, R. (1983) Changes in susceptibility to respiratory infection caused by exposure to photochemical oxidant pollutants. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 273-285. (Advances in modern environmental toxicology: v.5).

Ehrlich, R.; Findlay, J. C.; Fenters, J. D.; Gardner, D. E. (1977) Health effects of short-term inhalation of nitrogen dioxide and ozone mixtures. Environ. Res. 14: 223-231.

Ehrlich, R.; Findlay, J. C.; Gardner, D. E. (1979) Effects of repeated exposures to peak concentrations of nitrogen dioxide and ozone on resistance to streptococcal pneumonia. J. Toxicol. Environ. Health 5: 631-642.

Elsayed, N. M.; Mustafa, M. G.; Postlethwait, E. M. (1982a) Age-dependent pulmonary response of rats to ozone exposure. J. Toxicol. Environ. Health 9: 835-848.

Elsayed, N. M.; Hacker, A. D.; Kuehn, K.; Mustafa, M. G.; Schrauzer, G. N. (1983) Dietary antioxidants and the biochemical response to oxidant inhalation. II. Influence of dietary selenium on the biochemical effects of ozone exposure in mouse lung. Toxicol. Appl. Pharmacol. 71: 398-406.

Elsayed, N.; Hacker, A.; Mustafa, M.; Kuehn, K.; Schrauzer, G. (1982b) Effects of decreased glutathione peroxidase activity on the pentose phosphate cycle in mouse lung. Biochem. Biophys. Res. Commun. 104: 564-569.

Emik, L. O.; Plata, R. L. (1969) Depression of running activity in mice by exposure to polluted air. Arch. Environ. Health 18: 574-579.

Emik, L. O.; Plata, R. L.; Campbell, K. I.; Clarke, G. L. (1971) Biological effects of urban air pollution. Riverside summary. Arch. Environ. Health 23: 335-342.

Engel, L. A.; Macklem, P. T. (1977) Gas mixing and distribution in the lung. In: Widdicombe, J. G., ed. International Review of Physiology. Vol. 14: Respirat. Physiol. II, Widdicombe, J. G., (ed.); University Park Press, p. 321.

Erdman, H. E.; Hernandez, T. (1982) Adult toxicity and dominant lethals induced by ozone at specific stages in spermatogenesis in Drosophila virilis. Environ. Mutagen. 4: 657-666.

Eustis, S. L.; Schwartz, L. W.; Kosch, P. C.; Dungworth, D. L. (1981) Chronic bronchiolitis in nonhuman primates after prolonged ozone exposure. Am. J. Pathol. 105: 121-137.

Evans, M. J.; Stephens, R. J.; Freeman, G. (1976c). Renewal of pulmonary epithelium following oxidant injury. In: Bouhuys, A., ed. Lung cells in disease. New York, NY: Elsevier Press; pp. 165-178.

Evans, M. J.; Johnson, L. V.; Stephens, R. J.; Freeman, G. (1976b) Cell renewal in the lungs of rats exposed to low levels of ozone. Exp. Mol. Pathol. 24: 70-83.

Evans, M. J.; Johnson, L. V.; Stephens, R. J.; Freeman, G. (1976a) Renewal of the terminal bronchiolar epithelium in the rat following exposure to NO_2 or O_3. Lab. Invest. 35: 246-257.

Evans, M. J.; Mayr, W.; Bils, R. F.; Loosli, C. G. (1971) Effects of ozone on cell renewal in pulmonary alveoli of aging mice. Arch. Environ. Health 22: 450-453.

Fabbri, L. M.; Aizawa, H.; Alpert, S. E.; Walters, E. H.; O'Byrne, P. M.; Gold, B. D.; Nadel, J. A.; Holtzman, M. J. (1984) Airway hyperresponsiveness and changes in cell counts in bronchoalveolar lavage after ozone exposure in dogs. Am. Rev. Respir. Dis. 129: 288-291.

Fairchild, E. J. (1963) Neurohumoral factors in injury from inhaled irritants. Arch. Environ. Health 6: 85-92.

Fairchild, E. J. (1967) Tolerance mechanisms: determination of lung responses to injurious agents. Arch. Environ. Health 14: 111-126.

Fairchild, G. A. (1974) Ozone effect on respiratory deposition of vesicular stomatitis virus aerosols. Am. Rev. Respir. Dis. 109: 446-451.

Fairchild, G. A. (1977) Effects of ozone and sulfur dioxide on virus growth in mice. Arch. Environ. Health 32: 28-33.

Fairchild, E. J.; Graham, S. L. (1963) Thyroid influence on the toxicity of respiratory irritant gases, ozone and nitrogen dioxide. J. Pharmacol. Exp. Ther. 139: 177-184.

Fairchild, E. J.; Murphy, S. D.; Stokinger, H. E. (1959) Protection by sulfur compounds against the air pollutants ozone and nitrogen dioxide. Science (Washington, DC) 130: 861-862.

Fairchild, E. J.; Graham, S. L.; Hite, M.; Killens, R.; Scheel, L. D. (1964) Changes in thyroid I^{131} activity in ozone-tolerant and ozone-susceptible rats. Toxicol. Appl. Pharmacol. 6: 607-613.

Fetner, R. H. (1958) Chromosome breakage in Vicia faba by ozone. Nature (London) 181: 504-505.

Fetner, R. H. (1962) Ozone-induced chromosome breakage in human cell cultures. Nature (London) 194: 793-794.

Fetner, R. H. (1963) Mitotic inhibition induced in grasshopper neuroblasts by exposure to ozone. Brooks Air Force Base, TX: USAF School of Aerospace Medicine; Document no. SAM-TOR 63-39. Available from: NTIS, Springfield, VA; AD489014.

Filser, S. G.; Bolt, H. M.; Muliawon, H.; Kappus, H. (1983) Quantitative evaluation of ethane and n-pentane as indicators of lipid peroxidation in vivo. Arch. Toxicol. 52: 135-147.

Fletcher, B. L.; Tappel, A. L. (1973) Protective effects of dietary alphatocopherol in rats exposed to toxic levels of ozone and nitrogen dioxide. Environ. Res. 6: 165-175.

Fletcher, C. M.; Gilson, J. G.; Hugh-Jones, P.; Scadding, J. G. (1959) Terminology, definitions, and classification of chronic pulmonary emphysema and related conditions: a report of the conclusions of a CIBA guest symposium. Thorax 14: 286-299.

Frager, N. B.; Phalen, R. F.; Kenoyer, J. L. (1979) Adaptations to ozone in reference to mucociliary clearance. Arch. Environ. Health 34: 51-57.

Freeman, B. A.; Mudd, J. B. (1981) Reaction of ozone with sulfhydryls of human erythrocytes. Arch. Biochem. Biophys. 208: 212-220.

Freeman, B. A.; Sharman, M. C.; Mudd, J. B. (1979) Reaction of ozone with phospholipid vesicles and human erythrocyte ghosts. Arch. Biochem. Biophys. 197: 264-272.

Freeman, G.; Stephens, R. J.; Coffin, D. L.; Stara, J. F. (1973) Changes in dog's lungs after long-term exposure to ozone. Arch. Environ. Health 26: 209-216.

Freeman, G.; Crane, S. C.; Furiosi, N. J.; Stephens, R. J.; Evans, M. J.; Moore, W. D. (1972) Covert reduction in ventilatory surface in rats during prolonged exposure to subacute nitrogen dioxide. Am. Rev. Respir. Dis. 106: 563-579.

Freeman, G.; Juhos, L. T.; Furiosi, N. J.; Mussenden, R.; Stephens, R. J.; Evans, M. J. (1974) Pathology of pulmonary disease from exposure to interdependent ambient gases (nitrogen dioxide and ozone). Arch. Environ. Health 29: 203-210.

Friberg, L.; Holman, B.; Rylander, R. (1972) Animal lung reactions after inhalation of lead and ozone. Environ. Physiol. Biochem. 2: 170-178.

Friedman, M.; Gallo, J. M.; Nichols, H. P.; Bromberg, P. A. (1983) Changes in inert gas rebreathing parameters after ozone exposure in dogs. Am. Rev. Respir. Dis. 128: 851-856.

Fukase, O.; Watanabe, H.; Isomura, K. (1978) Effects of exercise on mice exposed to ozone. Arch. Environ. Health 33: 198-200.

Fukase, O.; Isomura, K.; Watanabe, H. (1975) Effect of ozone on glutathione in vivo. Taiki Osen Kenkyu 10: 58-62.

Gardner, D. E. (1981) Effects of environmental chemicals on host defense responses of the lung. In: Dean, J. H.; Padarathsingh, M., eds. Biological relevance of immune suppression as induced by genetic, therapeutic and environmental factors: second in a series of technology assessment workshops; November 1979; Williamsburg, VA. New York, NY: Van Nostrand Reinhold Co.; pp. 275-287.

Gardner, D. E. (1982a) Use of experimental airborne infections for monitoring altered host defenses. EHP Environ. Health Perspect. 43: 99-107.

Gardner, D. E. (1982b) Effects of gases and airborne particles on lung infections. In: McGrath, J. J.; Barnes, C. D. eds. Air pollution - physiological effects. New York, NY: Academic Press, Inc.; pp. 47-79.

Gardner, D. E.; Ehrlich, R. (1983) Introduction to host defense sessions. In: Lee, S.D.; Mustafa, M.G.; Mehlman, M.A., eds. International symposium on biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 255-261. (Advances in modern environmental toxicology: v. 5).

Gardner, D. E.; Graham, J. A. (1977) Increased pulmonary disease mediated through altered bacterial defenses. In: Sanders, C. L.; Schneider, R. P.; Dagle, G. E.; Ragen, H. A., eds. Pulmonary macrophage and epithelial cells: proceedings of the sixteenth annual Hanford biology symposium; September 1976; Richland, WA. Washington, DC: Energy Research and Development Administration; pp. 1-21. (ERDA symposium series: 43).

Gardner, D. E.; Illing, J. W.; Miller, F. J.; Coffin, D. L. (1974) The effect of ozone on pentobarbital sleeping time in mice. Res. Commun. Chem. Pathol. Pharmacol. 9: 689-700.

Gardner, D. E.; Miller, F. J.; Illing, J. W.; Kirtz, J. M. (1977) Increased infectivity with exposure to ozone and sulfuric acid. Toxicol. Lett. 1: 59-64.

Gardner, D. E.; Pfitzer, E. A.; Christian; R. T.; Coffin, D. L. (1971) Loss of protective factor for alveolar macrophages when exposed to ozone. Arch. Intern. Med. 127: 1078-1084.

Gardner, D. E.; Lewis, T. R.; Alpert, S. M.; Hurst, D. J.; Coffin, D. L. (1972) The role of tolerance in pulmonary defense mechanisms. Arch. Environ. Health 25: 432-438.

Gelmont, D.; Stein, R. A.; Mead, J. F. (1981) The bacterial origin of rat breath pentane. Biochem. Biophys. Res. Commun. 102: 932-936.

Gershwin, L. J.; Osebold, J. W.; Zee, Y. C. (1981) Immunoglobulin E-containing cells in mouse lung following allergen inhalation and ozone exposure. Int. Arch. Allergy Appl. Immunol. 65: 266-277.

Gertner, A.; Bromberger-Barnea, B.; Traystman, R.; Menkes, H. (1983c) Effects of ozone in peripheral lung reactivity. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 55: 777-784.

Gertner, A.; Bromberger-Barnea, B.; Dannenberg, A. M., Jr.; Traystman, R.; Menkes, H. (1983a) Responses of the lung periphery to 1.0 ppm ozone. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 55: 770-776.

Gertner, A.; Bromberger-Barnea, B.; Traystman, R.; Berzon, D.; Menkes, H. (1983b) Responses of the lung periphery to ozone and histamine. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 54: 640-646.

Gildemeister, M. (1921) Uber Kampfgasvergiftungen. In: Laquer, E.; Magus, R., eds. Experimental and theoretical bases for the therapy of phosgene sickness. Z. Gesamte Exper. Med. 13: 284-296.

Gillespie, J. R. (1980) Review of the cardiovascular and pulmonary function studies on beagles exposed for 68 months to auto exhaust and other air pollutants In: Stara, J. F.; Dungworth, D. L.; Orthoefer, J. C.; Tyler, W. S., eds. Long-term effects of air pollutants in canine species. Cincinnati, Ohio: U.S. Environmental Protection Agency; pp. 115-154; EPA 600/8-80-014.

Giri, S. N.; Hollinger, M. A.; Schiedt, M. J. (1980) The effects of ozone and paraquat on PGF_{2a} and PGE_2 levels in plasma and combined pleural effusion and lung lavage of rats. Environ. Res. 21: 467-476.

Giri, S. N.; Benson, J.; Siegel, D. M.; Rice, S. A.; Schiedt, M. (1975) Effects of pretreatment with anti-inflammatory drugs on ozone-induced damage in rats. Proc. Soc. Exp. Biol. Med. 150: 810-814.

Goldstein, B. D. (1973) Hydrogen peroxide in erythrocytes. Detection in rats and mice inhaling ozone. Arch. Environ. Health 26: 279-280.

Goldstein, B. D.; Balchum, O. J. (1974) Modification of the response of rats to lethal levels of ozone by enzyme-inducing agents. Toxicol. Appl. Pharmacol. 27: 330-335.

Goldstein, B. D.; McDonagh, E. M. (1975) Effect of ozone on cell membrane protein fluorescence. I. *In vitro* studies utilizing the red cell membrane. Environ. Res. 9: 179-186.

Goldstein, B. D.; Lai, L. Y.; Cuzzi-Spada, R. (1974) Potentiation of complement-dependent membrane damage by ozone. Arch. Environ. Health 28: 40-42.

Goldstein, B. D.; Hamburger, S. J.; Falk, G. W.; Amoruso, M. A. (1977) Effect of ozone and nitrogen dioxide on the agglutination of rat alveolar macrophages by concanavalin A. Life Sci. 21: 1637-1644.

Goldstein, B. D.; Solomon, S.; Pasternack, B. S.; Bickers, D. R. (1975) Decrease in rabbit lung microsomal cytochrome P-450 levels following ozone exposure. Res. Commun. Chem. Pathol. Pharmacol. 10: 759-762.

Goldstein, B. D.; Pearson, B.; Lodi, C.; Buckley, R. D.; Balchum, O. J. (1968) The effect of ozone on mouse blood *in vivo*. Arch. Environ. Health 16: 648-650.

Goldstein, B. D.; Levine, M. R.; Cuzzi-Spada, R.; Cardenas, R.; Buckley, R. D.; Balchum, O. S. (1972) *p*-aminobenzoic acid as a protective agent in ozone toxicity. Arch. Environ. Health 24: 243-247.

Goldstein, E.; Eagle, M. C.; Hoeprich, P. (1972) Influence of ozone on pulmonary defense mechanisms of silicotic mice. Arch. Environ. Health 24: 444-448.

Goldstein, E.; Gibson, J. B.; Tassan, C.; Lippert, W. (1978a) Effect of levamisole on alveolar macrophage function. Am. Rev. Respir. Dis. 117: 273.

Goldstein, E.; Tyler, W. S.; Hoeprich, P. D.; Eagle, C. (1971a) Ozone and the antibacterial defense mechanisms of the murine lung. Arch. Intern. Med. 128: 1099-1102.

Goldstein, E.; Tyler, W. S.; Hoeprich, P. D.; Eagle, C. (1971b) Adverse influence of ozone on pulmonary bactericidal activity of murine lungs. Nature (London) 229: 262-263.

Goldstein, E.; Warshauer, D.; Lippert, W.; Tarkington, B. (1974) Ozone and nitrogen dioxide exposure. Arch. Environ. Health 28: 85-90.

Goldstein, E.; Bartlema, H. C.; van der Ploeg, M.; van Duijn, P.; van der Stap, J. G. M. M.; Lippert, W. (1978b) Effect of ozone on lysosomal enzymes of alveolar macrophages engaged in phagocytosis and killing of inhaled Staphylococcus aureus. J. Infect. Dis. 138: 299-311.

Gooch, P. C.; Creasia, D. A.; Brewen, J. G. (1976) The cytogenetic effect of ozone: inhalation and in vitro exposures. Environ. Res. 12: 188-195.

Gordon, T.; Amdur, M. O. (1980) Effects of ozone on respiratory response of guinea pigs to histamine. J. Toxicol. Environ. Health 6: 185-195.

Gordon, T.; Taylor, B. F.; Amdur, M. O. (1981) Ozone inhibition of tissue cholinesterase in guinea pigs. Arch. Environ. Health 36: 284-288.

Graham, J. A. (1979) Alteration of hepatic xenobiotic metabolism by ozone. Durham, NC: Duke University. Ph.D. Dissertation.

Graham, J. A.; Menzel, D. B.; Miller, F. J.; Illing, J. W.; Gardner, D. E. (1981) Influence of ozone on pentobarbital-induced sleeping time in mice, rats, and hamsters. Toxicol. Appl. Pharmacol. 61: 64-73.

Graham, J. A.; Menzel, D. B.; Miller, F. J.; Illing, J. W.; Gardner, D. E. (1982a) Effect of ozone on drug-induced sleeping time in mice pretreated with mixed-function oxidase inducers and inhibitors. Toxicol. Appl. Pharmacol. 62: 489-497.

Graham, J. A.; Menzel, D. B.; Mole, M. L.; Miller, F. J.; Gardner, D. E. (1983b) Influence of ozone on pentobarbital pharmacokinetics in mice. Toxicol. Lett. (In Press).

Graham, J. A.; Miller, F. J.; Gardner, D. E.; Ward, R.; Menzel, D. B. (1982b) Influence of ozone and nitrogen dioxide on hepatic microsomal enzymes in mice. J. Toxicol. Environ. Health 9: 849-856.

Graham, J. A.; Menzel, D. B.; Miller, F. J.; Illing, J. W.; Ward, R.; Gardner, D.E. (1983a) Influence of ozone on xenobiotic metabolism. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 95-117. (Advances in modern environmental toxicology: v. 5).

Gregory, A. R.; Ripperton, L. A.; Miller, B. (1967) Effect of monatal thymectomy on the development of ozone tolerance in mice. Am. Ind. Hyg. Assoc. J. 28: 278-283.

Grose, E. C.; Gardner, D. E.; Miller, F. J. (1980) Response of ciliated epitheluim to ozone and sulfuric acid. Environ. Res. 22: 377-385.

Grose, E. C.; Richards, J. H.; Illing, J. W.; Miller, F. J.; Davies, D. W.; Graham, J. A.; Gardner, D. E. (1982) Pulmonary host defense responses to inhalation of sulfuric acid and ozone. J. Toxicol. Environ. Health 10: 351-362.

Gross, E. A.; Swenberg, J. A.; Fields, S.; Popp, J. A. (1982) Comparative morphometry of the nasal cavity in rats and mice. J. Anat. 135: 83-88.

Gross, P.; Scheel, L. D.; Stokinger, H. E. (1965) Ozone toxicity studies; destruction of alveolar septa-a precursor of emphysema? In: Mitchell, R. S., ed. The pathogenesis of the chronic obstructive bronchopulmonary disease: seventh annual conference on research in emphysema; June 1964; Aspen, CO. Basel, Switzerland: S. Karger, AG; pp. 376-381. (Progress in research in emphysema and chronic bronchitis: v. 2; Medicina Thoracalis: v. 22, nos. 1-3).

Gross, S.; Melhorn, P. K. (1972) Vitamin E red cell lipids and red cell stability in prematurity. Ann. N. Y. Acad. Sci. 203: 141-162.

Guerrero, R. R.; Rounds, D. E.; Olson, R. S.; Hackney, J. D. (1979) Mutagenic effects of ozone on human cells exposed _in vivo_ and _in vitro_ based on sister chromatid exchange analysis. Environ. Res. 18: 336-346.

Hadley, J. G.; Gardner, D. E.; Coffin D. L.; Menzel, D. B. (1977) Enhanced binding of autologous cells to the macrophage plasma membrane as a sensitive indicator of pollutant damage. In: Sanders, C. L.; Schneider, R. P.; Dagle G. E.; Ragan, H. A., eds. Pulmonary macrophage and epithelial cells: proceedings of the sixteenth annual Hanford biology symposium; September 1976; Richland, WA. Washington, DC: Energy Research and Development Administration; pp. 1-21. (ERDA symposium series: 43).

Halliwell, B. (1982) Production of superoxide, hydrogen peroxide and hydroxyl radicals by phagocytic cells: a cause of chronic inflammatory disease? Cell Biol. Int. Rep. 6: 529-542.

Hamburger, S. J.; Goldstein, B. D. (1979) Effect of ozone on the agglutination of erythrocytes by concanavalin A. Part I: studies in rats. Environ. Res. 19: 292-298.

Hamburger, S. J.; Goldstein, B. D.; Buckley, R. D.; Hackney, J. D.; Amoruso, M. A. (1979) Effect of ozone on the agglutination of erythrocytes by concanavalin A. Part II: study of human subjects receiving supplemental vitamin E. Environ. Res. 19: 299-305.

Hamelin, C.; Chung, Y. S. (1974) Ozone resistance in _Escherichia coli_. I. Relations with some DNA repair mechanisms = Resistance à l'ozone chez _Escherichia coli_. I. Relations avec certain mécanismes de réparation de l'ADN. Mol. Gen. Genet. 129: 177-184.

Hamelin, C.; Chung, Y. S. (1975a) The effect of low concentrations of ozone on _Escherichia coli_ chromosome. Mutat. Res. 28: 131-132.

Hamelin, C.; Chung, Y. S. (1975b) Characterization of mucoid mutants of Escherichia coli K-12 isolated after exposure to ozone. J. Bacteriol. 122: 19-24.

Hamelin, C.; Chung, Y.S. (1978) Role of the pol, rec, and DNA gene products in the repair of lesions produced in Escherichia coli DNA by ozone. Stud. Biophys. 68: 229-335.

Hamelin, C.; Sarhan, F.; Chung, Y. S. (1977a) Ozone-induced DNA degradation in different DNA polymerase I mutants of E coli K12. Biochem. Biophys. Res. Commun. 77: 220-224.

Hamelin, C.; Sarhan, F.; Chung, Y. S. (1977b) DNA degradation caused by ozone in mucoid mutants of Escherichia coli K12. FEMS Microbiol. Lett. 2: 149-151.

Hammond, P. B.; Beliles, R. P. (1980) Metals: ch. 17. In: Doull, J.; Klaassen, C. D.; Amdur, M. O., eds. Toxicology, the Basic Science of Poisons. New York, NY: Macmillan Press Company, Inc.; pp. 409-467.

Hathaway, J. A.; Terrill, R. E. (1962) Metabolic effects of chronic ozone exposure on rats. Am. Ind. Hyg. Assoc. J. 23: 392-395.

Hattori, K.; Kato, N.; Kinoshita, M.; Kinoshita, S.; Sunada, T. (1963) Protective effect of ozone in mice against whole-body x-irradiation. Nature (London) 198: 1220.

Hayes, W. J., Jr. (1975) Toxicology of Pesticides. Baltimore, MD: William and Wilkins Company; pp. 118-127.

Henschler, D. (1960). Protective effect of previous treatment with low gas concentrations against lethal pulmonary edema from irritant gas. Naunyn Schmiedeberg's Arch. Exper. Pathol. Pharmakol. 238: 66-67.

Hesterberg, T. W.; Last, J. A. (1981) Ozone-induced acute pulmonary fibrosis in rats. Prevention of increased rates of collagen synthesis by methylprednisolone. Am. Rev. Respir. Dis. 123: 47-52.

Hilding, D. A.; Hilding, A. C. (1966) Ultrastructure of tracheal cilia and cell during regeneration. Ann. Otol. Rhinol. Laryngol. 75: 281-294.

Holtzman, M. J.; Fabbri, L. M.; Skoogh, B.-E.; O'Byrne, P. M.; Walters, E. H.; Aizawa, H.; Nadel, J. A. (1983a) Time course of airway hyperresponsiveness induced by ozone in dogs. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 55: 1232-1236.

Holtzman, M. J.; Fabbri, L. M.: O'Byrne, P. M.; Gold, B. D.; Aizawa, H.; Walters, S. E.; Alpert, S. E.; Nadel, J. A. (1983b) Importance of airway inflammation for hyperresponsiveness induced by ozone. Am. Rev. Respir. Dis. 127: 686-690.

Holzman, R. S.; Gardner, D. E.; Coffin, D. L. (1968) In vivo inactivation of lysozyme by ozone. J. Bacteriol. 96: 1562-1566.

Hu, P. C.; Miller, F. J.; Daniels, M. J.; Hatch, G. E.; Graham, J. A.; Gardner, D. E.; Selgrade, M. K. (1982) Protein accumulation in lung lavage fluid following ozone exposure. Environ. Res. 29: 377-388.

Huber, G. L.; Mason, R. J.; LaForce, M.; Spencer, N. J.; Gardner, D. E.; Coffin, D. L. (1971) Alterations in the lung following the administration of ozone. Arch. Intern. Med. 128: 81-87.

Hueter, F. G.; Contner, G. L.; Busch, K. A.; Hinners, R. G. (1966) Biological effects of atmospheres contaminated by auto exhaust. Arch. Environ. Health 12: 553-560.

Hurst, D. J.; Coffin, D. L. (1971) Ozone effect on lysosomal hydrolases of alveolar macrophages in vitro. Arch. Intern. Med. 127: 1059-1063.

Hurst, D. J.; Gardner, D. E.; Coffin, D. L. (1970) Effect of ozone on acid hydrolases of the pulmonary alveolar macrophage. Res. J. Reticuloendothel. Soc. 8: 288-300.

Hussain, M. Z.; Cross, C. E.; Mustafa, M. G.; Bhatnagar, R. S. (1976b) Hydroxyproline contents and prolyl hydroxylase activities in lungs of rats exposed to low levels of ozone. Life Sci. 18: 897-904.

Hussain, M. Z.; Mustafa, M. G.; Chow, C. K.; Cross, C. E. (1976a) Ozone-induced increase of lung proline hydroxylase activity and hydroxyproline content. Chest 69 (Suppl. 2): 273-275.

Hyde, D.; Orthoefer, J.; Dungworth, D.; Tyler, W.; Carter, R.; Lum, H. (1978) Morphometric and morphologic evaluation of pulmonary lesions in beagle dogs chronically exposed to high ambient levels of air pollutants. Lab. Invest. 38: 455-469.

Ibrahim, A. L.; Zee, Y. C.; Osebold, J. W. (1976) The effects of ozone on the respiratory epithelium and alveolar macrophages of mice. I. Interferon production. Proc. Soc. Exp. Biol. Med. 152: 483-488.

Ibrahim, A. L.; Zee, Y. C.; Osebold, J. W. (1980) The effects of ozone on the respiratory epithelium of mice. II. Ultrastructural alterations. J. Environ. Pathol. Toxicol. 3: 251-258.

Ikematsu, T. (1978) Influence of ozone on rabbit's tonsils--observations of the surface of the tonsil with scanning electron microscope. Nippon Jibi Inkoka Gakkai Kaiho 81: 1447-1458.

Illing, J. W.; Miller, F. J.; Gardner, D. E. (1980) Decreased resistance to infection in exercised mice exposed to NO_2 and O_3. J. Toxicol. Environ. Health 6: 843-851.

Inoue, H.; Sato, S.; Hirose, T.; Kikuchi, Y.; Ubukata, T.; Nagashima, S.; Sasaki, T.; Takishima, T. (1979) A comparative study between functional and pathologic alterations in lungs of rabbits exposed to an ambient level of ozone: functional aspects. Nikkyo Shikkai-Shi 17: 288-296.

Ishidate, M., Jr.,; Yoshikawa, K. (1980) Chromosome aberration tests with Chinese hamster cells in vitro with and without metabolic activation--a comparative study on mutagens and carcinogens. Arch. Toxicol. 4: 41-44.

Jegier, Z. (1973) Ozone as an air pollutant. Can. J. Public Health 64: 161-166.

Johnson, D. A. (1980) Ozone inactivation of human alpha 1-proteinase inhibitor. Am. Rev. Respir. Dis. 121: 1031-1038.

Johnson, B. L.; Orthoefer, J. G.; Lewis, T. R.; Xintaras, C. (1976) The effect of ozone on brain function. In: Finkel, A. J.; Duel, W. C., eds. Clinical implications of air pollution research: proceedings of the 1974 air pollution medical research conference; December 1974; San Francisco, CA. Acton, MA: Publishing Sciences Group, Inc.; pp. 233-245.

Johnson, K. I.; Fantone, J. C., III; Kaplan, J.; Ward, P. A. (1981) In vivo damage of rat lungs by oxygen metabolites. Clin. Invest. 67: 983-993.

Juhos, L. T.; Evans, M. J.; Missenden-Harvey, R.; Furiosi, N. J.; Lapple, C. E.; Freeman, G. (1978) Limited exposure of rats to H_2SO_4 with and without O_3. J. Environ. Sci. Health C13: 33-47.

Kaplan, J.; Smaldone, G. C.; Menkes, H. A.; Swift, D. L.; Traystman, R. J. (1981) Response of collateral channels to histamine: lack of vagal effect. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 51: 1314-1319.

Kavlock, R.; Daston, G.; Grabowski, C. T. (1979) Studies on the developmental toxicity of ozone. I. Prenatal effects. Toxicol. Appl. Pharmacol. 48: 19-28.

Kavlock, R. J.; Meyer, E.; Grabowski, C. T. (1980) Studies on the developmental toxicity of ozone: postnatal effects. Toxicol. Lett. 5: 3-9.

Kawachi, T.; Yahagi, T.; Kada, T.; Tazima, Y.; Ishidate, M.; Sasaki, M.; Sugiyama, T. (1980) Cooperative programme on short-term assays for carcinogenicity in Japan. In: Montesano, R.; Bartsch, H.; Tomatis, L.; Davis, W., eds. Molecular and cellular aspects of carcinogen screening tests; June 1979; Hanover, West Germany. Lyon, France: International Agency for Research on Cancer; pp. 323-330. (IARC scientific publications: no. 27).

Kenoyer, J. L.; Phalen, R. F.; Davis, J. R. (1981) Particle clearance from the respiratory tract as a test of toxicity: effect of ozone on short and long term clearance. Exp. Lung Respir. 2: 111-120.

Kensler, C. J.; Battista, S. D. (1966) Chemical and physical factors affecting mammalian ciliary activity. Am. Rev. Respir. Dis. 93: 93-102.

Kesner, L.; Kindya, R. J.; Chan, P. C. (1979) Inhibition of erythrocyte membrane (Na^++K^+)-activated ATPase by ozone-treated phospholipids. J. Biol. Chem. 254: 2705-2709.

Kimura, A.; Goldstein, E. (1981) Effect of ozone on concentrations of lysozyme in phagocytizing alveolar macrophages. J. Infect. Dis. 143: 247-251.

Kindya, R. J.; Chan, P. C. (1976) Effect of ozone on erythrocyte membrane adenosine triphosphatase. Biochim. Biophys. Acta 429: 608-615.

Klebanoff, S. J.; Clark, R. A. (1975) Hemolysis and iodination of erythrocyte components by a gycloperoxidase-mediated system. Blood 45: 699-707.

Kliment, V. (1973) Similarity and dimensional analysis, evaluation of aerosol deposition in the lungs of laboratory animals and man. Folia Morphol. 21: 59-64.

Konigsberg, A. S.; Bachman, C. H. (1970) Ozonized atmosphere and gross motor activity of rats. Int. J. Biometeorol. 14: 261-266.

Koontz, A. E.; Heath, R. L. (1979) Ozone alteration of transport of cations and the Na$^+$/K$^+$ ATPase in human erythrocytes. Arch. Biochem. Biophys. 198: 493-500.

Kotin, P.; Thomas, M. (1957) Effect of air contaminants on reproduction and offspring survival in mice. AMA Arch. Ind. Health 16: 411-413.

Kulle, T. J.; Cooper, G. P. (1975) Effects of formaldehyde and ozone on the trigeminal nasal sensory system. Arch. Environ. Health 30: 237-243.

Kyei-Aboagye, K.; Hazucha, M.; Wyszogrodski, I.; Rubinstein, D.; Avery, M. E. (1973) The effect of ozone exposure *in vivo* on the appearance of lung tissue lipids in the endobronchial lavage of rabbits. Biochem. Biophys. Res. Commun. 54: 907-913.

La Belle, C. W.; Long, J. E.; Christofano, E. E. (1955) Synergistic effects of aerosols. Particulates as carriers of toxic vapors. AMA Arch. Ind. Health 11: 297-304.

Landahl, H. D. (1950) On the removal of air-borne droplets by the human respiratory tract. I. The lung. Bull. Math. Biophys. 12: 43-56.

Larkin, E.C.; Goheen, S.C.; Rao, G.A. (1983) Morphology and fatty acid composition of erythrocytes from monkeys exposed to ozone for one year. Environ. Res. 32: 445-454.

Larkin, E. C.; Kimzey, S. L.; Siler, K. (1978) Response of the rat erythrocyte to ozone exposure. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 45: 893-898.

Last, J. A.; Cross, C. E. (1978) A new model for health effects of air pollutants: evidence for synergistic effects of mixtures of ozone and sulfuric acid aerosols on rat lungs. J. Lab. Clin. Med. 91: 328-339.

Last, J. A.; Greenberg, D. B. (1980) Ozone-induced alterations in collagen metabolism of rat lungs. II. Long-term exposure. Toxicol. Appl. Pharmacol. 55: 108-114.

Last, J. A.; Kaizu, T. (1980) Mucus glycoprotein secretion by tracheal explants: effects of pollutants. EHP Environ. Health Perspect. 35: 131-138.

Last, J. A.; Greenberg, D. B.; Castleman, W. L. (1979) Ozone-induced alterations in collagen metabolism of rat lungs. Toxicol. Appl. Pharmacol. 51: 247-258.

Last, J. A.; Dasgupta, P. K.; DeCesare, K.; Tarkington, B.K. (1982) Inhalation toxicology of ammonium persulfate, an oxidant aerosol, in rats. Toxicol. Appl. Pharmacol. 63: 257-263.

Last, J. A.; Jennings, M. D.; Schwartz, L. W.; Cross, C. E. (1977) Glycoprotein secretion by tracheal explants cultured from rats exposed to ozone. Am. Rev. Respir. Dis. 116: 695-703.

Lee, L.-Y.; Bleecker, E. R.; Nadel, J. A. (1977) Effect of ozone on bronchomotor response to inhaled histamine aerosol in dogs. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 43: 626-631.

Lee, L.-Y.; Dumont, C.; Djokic, T. D.; Menzel, T. E.; Nadel, J. A. (1979) Mechanism of rapid shallow breathing after ozone exposure in conscious dog. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 46: 1108-1109.

Lee, L.-Y.; Djokic, T. D.; Dumont, C.; Graf, P. D.; Nadel, J. A. (1980) Mechanism of ozone-induced tachypneic response to hypoxia and hypercapnia in conscious dogs. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 48: 163-168.

Lewis, T. R.; Hueter, F. G.; Busch, K. A. (1967) Irradiated automobile exhaust: its effects on the reproduction of mice. Arch. Environ. Health 15:26-35.

Lewis, T. R.; Moorman, W. J.; Yang, Y.; Stara, J. F. (1974) Long-term exposure to auto exhaust and other pollutant mixtures. Effects on pulmonary function in the beagle. Arch. Environ. Health 29:102-106.

Ling, N. R.; Kay, J. F. (1975) Lymphocyte Stimulation. North-Holland Publishing Co.

Lum, H.; Schwartz, L. W.; Dungworth, D. L.; Tyler, W. S. (1978) A comparative study of cell renewal after exposure to ozone or oxygen. Response of terminal bronchiolar epithelium in the rat. Am. Rev. Respir. Dis. 118: 335-345.

Lunan, K. D.; Short, P.; Negi, D.; Stephens, R. L. (1977) Glucose-6-phosphate dehydrogenase response of postnatal lungs to NO_2 and O_3. In: Sanders, C. L.; Schneider, R. P.; Dagle, G. E.; Ragan, H. A., eds. Pulmonary macrophage and epithelial cells: proceedings of the sixteenth annual Hanford biology symposium; September 1976; Richland, WA. Washington, DC: Energy Research and Development Administration; pp. 236-247. (ERDA symposium series: 43).

MacLean, S. A.; Longwell, A. C.; Blogoslawski, W. J. (1973) Effects of ozone-treated seawater on the spawned, fertilized, meiotic, and cleaving eggs of the commercial American Oyster. Mutat. Res. 21: 283-285.

MacRae, W. D.; Stich, H. F. (1979) Induction of sister chromatid exchanges in Chinese hamster ovary cells by Thiol and hydrazene compounds. Mutat. Res. 68: 351-365.

Martin, C. J.; Boatman, E. S.; Ward, G. (1983) Mechanical properties of alveolar wall after pneumonectomy and ozone exposure. J. Appl. Physiol. Respir. Environ. Exercise Physiol. 54: 785-788.

Matsumura, Y. (1970) The effects of ozone, nitrogen dioxide, and sulfur dioxide on the experimentally induced allergic respiratory disorder in guinea pigs. III. The effect on the occurrence of dyspneic attacks. Am. Rev. Respir. Dis. 102: 444-447.

Matsumura, Y., Mizuno, K.; Miyamoto, T.; Suzuki, T.; Oshima, Y. (1972) The effects of ozone, nitrogen dioxide and sulfur dioxide on the experimentally induced allergic respiratory disorders in guinea pigs. IV. Effects on respiratory sensitivity to inhaled acetylcholine. Am. Rev. Respir. Dis. 105: 262-267.

Matzen, R. N. (1957a) Development of tolerance to ozone in reference to pulmonary edema. Am. J. Physiol. 190: 84-88.

Matzen, R. N. (1957b) Effect of vitamin C and hydrocortisone on the pulmonary edema produced by ozone in mice. J. Appl. Physiol. 11: 105-109.

McAllen, S. J.; Chiu, S. P.; Phalen, R. F.; Rasmussen, R. E. (1981) Effect of in vivo ozone exposure on in vitro pulmonary alveolar macrophage mobility. J. Toxicol. Environ. Health 7: 373-381.

McCord, J. M.; Fridovich, I. (1978) The biology and pathology of oxygen radicals. Ann. Intern. Med. 89: 122-127.

McJilton, C.; Thielke, J.; Frank, R. (1972) Ozone uptake model for the respiratory system. In: Abstracts of technical papers: American industrial hygiene conference; May 1972; San Francisco, CA. Am. Ind. Hyg. Assoc. J. 33(2): paper no. 45.

Meiners, B. A.; Peters, R. E.; Mudd, J. B. (1977) Effects of ozone on indole compounds and rat lung monoamine oxidase. Environ. Res. 14: 99-112.

Mellick, P. W.; Mustafa, M. G.; Tyler, W. S.; Dungworth, D. L. (1975) Morphologic and biochemical changes in primate lung due to low-level ozone exposure. Bull. Int. Union Against Tuberculosis 51: 565-567.

Mellick, P. W.; Dungworth, D. L.; Schwartz, L. W.; Tyler, W. S. (1977) Short-term morphologic effects of high ambient levels of ozone on lungs of rhesus monkeys. Lab. Invest. 36: 82-90.

Mendenhall, R. M.; Stokinger, H. E. (1959) Tolerance and cross-tolerance development to atmospheric pollutants ketene and ozone. J. Appl. Physiol. 14: 923-926.

Menzel, D. B. (1970) Toxicity of ozone, oxygen, and radiation. Ann. Rev. Pharmacol. 10: 379-394.

Menzel, D. B. (1971) Oxidation of biologically active reducing substances by ozone. Arch. Environ. Health 23: 149-153.

Menzel, D. B. (1976) The role of free radicals in the toxicity of air pollutants (nitrogen oxides and ozone). In: Pryor, W. A., ed. Free radicals in biology: v. II. New York, NY: Academic Press, Inc.; pp. 181-202.

Menzel, D. B. (1983) Metabolic effects of ozone exposure. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 47-55. (Advances in modern environmental toxicology: v. 5).

Menzel, D. B.; Anderson, W. G.; Abou-Donia, M. B. (1976) Ozone exposure modifies prostaglandin biosynthesis in perfused rat lungs. Res. Commun. Chem. Pathol. Pharmacol. 15: 135-147.

Menzel, D. B.; Donovan, D. H.; Sabransky, M. Dietary vitamin E and fat: effect on murine lung and red blood cell glutathione peroxidase activity. FASEB Meeting. 1978.

Menzel, D. B.; Roehm, J. N.; Lee, S. D. (1972) Vitamin E: the biological and environmental antioxidant. J. Agric. Food Chem. 20: 481-486.

Menzel, D. B.; Slaughter, R. J.; Bryant, A. M.; Jauregui, H. O. (1975a) Heinz bodies formed in erythrocytes by fatty acid ozonides and ozone. Arch. Environ. Health 30: 296-301.

Menzel, D. B.; Slaughter, R. J.; Bryant, A. M.; Jauregui, H. O. (1975b) Prevention of ozonide-induced Heinz bodies in human erythrocytes by vitamin E. Arch. Environ. Health 30: 234-236.

Menzel, D. B.; Slaughter, R.; Donavan, D.; Bryant, A. (1973) Fatty acid ozonides as the toxic agents on ozone inhalation. Pharmacologist 15: 239.

Menzel, D. B.; Smolko, E. D.; Gardner, D. E.; Graham, J. A. (1983) Frontiers in short-term testing of pneumotoxicants. In: Woodhead, ed. Short-term tests for environmentally-induced chronic health effects. Washington, D.C.: U.S. Environmental Protection Agency, Office of Research and Development; EPA-600/8-83-002.

Miller, F. J. (1977) A mathematical model of transport and removal of ozone in mammalian lungs. Raleigh, NC: North Carolina State University; Ph.D. thesis.

Miller, F. J. (1979) Biomathematical modeling applications in the evaluation of ozone toxicity: ch. 14. In: Lee, S. D.; Mudd, J. B., eds. Assessing toxic effects of environmental pollutants. Ann Arbor, MI: Ann Arbor Science Publishers, Inc.; pp. 263-286.

Miller, F. J.; Illing, J. W.; Gardner, D. E. (1978) Effect of urban ozone levels on laboratory-induced respiratory infections. Toxicol. Lett. 2: 163-169.

Miller, F. J.; McNeal, C. A.; Kirtz, J. M.; Gardner, D. E.; Coffin, D. L.; Menzel, D. B. (1979) Nasopharyngeal removal of ozone in rabbits and guinea pigs. Toxicology 14: 273-281.

Miller, S.; Ehrlich, R. (1958) Susceptibility to respiratory infections of animals exposed to ozone. J. Infect. Dis. 103: 145-149.

Mizoguchi, I.; Osawa, M.; Sato, Y.; Makino, K.; Yagyu, H. (1973) Studies on erythrocyte and photochemical smog. I. Effects of air pollutants on erythrocyte resistance. Taiki Osen Kenkyu 8: 414.

Montgomery, M. R.; Niewoehner, D. E. (1979) Oxidant-induced alterations in pulmonary microsomal mixed-function oxidation: acute effects of paraquat and ozone. J. Environ. Sci. Health C13: 205-219.

Moore, G. S.; Calabrese, E. J.; Grinberg-Funes, R. A. (1980) The C57L/J mouse strain as a model for extrapulmonary effects of ozone exposure. Bull. Environ. Contam. Toxicol. 25: 578-585.

Moore, G. S.; Calabrese, E. J.; Labato, F. J. (1981a) Erythrocyte survival in sheep exposed to ozone. Bull. Environ. Contam. Toxicol. 27: 126-138.

Moore, G. S.; Calabrese, E. J.; Schulz, E. (1981b) Effect of in vivo ozone exposure to dorset sheep, an animal model with low levels of erythrocyte glucose-6-phosphate dehydrogenase activity. Bull. Environ. Contam. Toxicol. 26: 273-280.

Moore, P. F.; Schwartz, L. W. (1981) Morphological effects of prolonged exposure to ozone and sulfuric acid aerosol on the rat lung. Exp. Mol. Pathol. 35: 108-123.

Moorman, W. J.; Chmiel, J. J.; Stara, J. F.; Lewis, T. R. (1973) Comparative decomposition of ozone in the nasopharynx of beagles. Acute vs. chronic exposure. Arch. Environ. Health 26: 153-155.

Morgan, M. S.; Frank, R. (1977) Uptake of pollutant gases by the respiratory system. In: Brain, J. D.; Proctor, D. F., eds. Respiratory defense mechanisms. Part I. New York, NY: Marcel Dekker, Inc.: pp. 157-189.

Mountain, J. T. (1963) Detecting hypersusceptibility to toxic substances, an appraisal of simple blood tests. Arch. Environ. Health 6: 357-365.

Mudd, J. B.; Freeman, B. A. (1977) Reaction of ozone with biological membranes. In: Lee, S. D., ed. Biochemical effects of environmental pollutants. Ann Arbor, MI: Ann Arbor Science Publishers, Inc.; pp. 97-133.

Mudd, J. B.; Leavitt, R.; Ongun, A.; McManus, T. T. (1969) Reaction of ozone with amino acids and proteins. Atmos. Environ. 3: 669-681.

Murphy, S. D. (1964) A review of effects on animals of exposure to auto exhaust and some of its components. J. Air Pollut. Control Assoc. 14: 303-308.

Murphy, S. D.; Leng, J. K.; Ulrich, C. E.; Davis, H. V. (1963) Effects on animals of exposure to auto exhaust. Arch. Environ. Health 7: 60-70.

Murphy, S. D.; Ulrich, C. E.; Frankowitz, S. H.; Xintaras, C. (1964) Altered function in animals inhaling low concentrations of ozone and nitrogen dioxide. Am. Ind. Hyg. Assoc. J. 25: 246-253.

Mustafa, M. G. (1975) Influence of dietary vitamin E on lung cellular sensitivity to ozone in rats. Nutr. Rep. Int. 11: 473-476.

Mustafa, M. G.; Cross, C. E. (1974) Effects of short-term ozone exposure on lung mitochondrial oxidative and energy metabolism. Arch. Biochem. Biophys. 162: 585-594.

Mustafa, M. G.; Lee, S. D. (1976) Pulmonary biochemical alterations resulting from ozone exposure. Ann. Occup. Hyg. 19: 17-26.

Mustafa, M. G.; Lee, S. D. (1979) Biological effects of environmental pollutants: methods for assessing biochemical changes. In: Lee, S. D.; Mudd, J. B., eds. Assessing toxic effects of environmental pollutants. Ann Arbor, MI: Ann Arbor Science Publishers, Inc.; pp. 105-120.

Mustafa, M. G.; Tierney, D. F. (1978) Biochemical and metabolic changes in the lung with oxygen, ozone, and nitrogen dioxide toxicity. Am. Rev. Respir. Dis. 118: 1061-1090.

Mustafa, M. G.; Faeder, E. J.; Lee, S. D. (1980) Biochemical basis of pulmonary response to ozone and nitrogen dioxide injury. In: Bhatnagar, R. S., ed. Molecular basis of environmental toxicity. Ann Arbor, MI: Ann Arbor Science Publishers, Inc.; pp. 151-172.

Mustafa, M. G.; Ospital, J. J.; Hacker, A. D. (1976) Effects of ozone and nitrogen dioxide exposure on lung metabolism. EHP Environ. Health Perspect. 16: 184 (Abstract).

Mustafa, M. G.; Elsayed, N. M.; Graham, J. A.; Gardner, D. E. (1983) Effects of ozone exposure on lung metabolism: influence of animal age, species, and exposure conditions. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 57-73. (Advances in modern environmental toxicology: v. 5).

Mustafa, M. G.; DeLucia, A. J.; York, G. K.; Arth, C.; Cross, C. E. (1973) Ozone interaction with rodent lung. II. Effects on oxygen consumption of mitochondria. J. Lab. Clin. Med. 82: 357-365.

Mustafa, M. G.; Hacker, A. D.; Ospital, J. J.; Hussain, M. Z.; Lee, S.D. (1977) Biochemical effects of environmental oxidants pollutants in animal lungs. In: Lee, S.D., ed. Biochemical effects of environmental pollutants. Ann Arbor, MI: Ann Arbor Science Publishers, Inc.; pp. 59-96.

Mustafa, M. G.; Elsayed, N. M.; Quinn, C. L.; Postlethwait, E. M.; Gardner, D. E.; Graham, J. A. (1982) Comparison of pulmonary biochemical effects of low level ozone exposure on mice and rats. J. Toxicol. Environ. Health 9: 857-865.

Mustafa, M. G.; Elsayed, N. M.; von Dohlen, F. M.; Hassett, C. M.; Postlethwait, E. M.; Quinn, C. L.; Graham, J. A.; Gardner, D. E. (1984) A comparison of biochemical effects of nitrogen dioxide, ozone, and their combination in mouse lung. Toxicol. Appl. Pharmacol. 72: (in press).

Nadel, J. A. (1977) Autoromic control of airway smooth muscle and airway secretions. Am. Rev. Respir. Dis. 115: 117-126.

Nakajima, T.; Kusumoto, S.; Tsubota, Y.; Yonekawa, E.; Yoshida, R.; Motomiya, K.; Ito, K.; Ide, G.; Ostu, H. (1972). Histopathological changes in the respiratory organs of mice exposed to photochemical oxidants and automobile exhaust gas. Osaka-Furitsu Koshu Eisei Kenkyusho Kenkyu Hokoku Rodo Eisei Hen 10:35-42.

Nasr, A. N. M. (1967) Biochemical aspects of ozone intoxication: a review. J. Occup. Med. 9: 589-597.

National Research Council. (1977) Drinking water and health. Washington, DC: National Academy of Sciences.

National Air Pollution Control Administration. (1970) Air quality criteria for photochemical oxidants. Washington, DC: U.S. Department of Health, Education and Welfare, Public Health Service; NAPCA publication no. AP-63. Available from: NTIS, Springfield, VA; PB190262.

National Institutes of Health. (1983) Supplement: comparative biology of the lung: workshop; June 1982. Am. Rev. Respir. Dis. Suppl. 128: (2, pt 2): S1-S91.

National Research Council. (1977) Toxicology: ch. 8. In: Ozone and other photochemical oxidants. Washington, DC: National Academy of Sciences, Committee on Medical and Biologic Effects of Environmental Pollutants; pp. 323-387.

Niewoehner, D. E.; Kleinerman, J.; Rice, D. B. (1974) Pathologic changes in the peripheral airways of young cigarette smokers. N. Engl. J. Med. 291: 755-758.

North Atlantic Treaty Organization. (1974) Air quality criteria for photochemical oxidants and related hydrocarbons: a report by the expert panel on air quality criteria. Brussels, Belgium: NATO, Committee on the Challenges of Modern Society; NATO/CCMS N. 29.

Oberst, F. W.; Comstock, C. C.; Hackley, E. B. (1954) Inhalation toxicity of ninety percent hydrogen peroxide vapor. AMA Arch. Ind. Hyg. Occup. Med. 10: 319-327.

Oomichi, S.; Kita, H. (1974) Effect of air pollutants on ciliary activity of respiratory tract. Bull. Tokyo Med. Dent. Univ. 21: 327-343.

Orthoefer, J. G.; Bhatnagar, R. S.; Rahman, A.; Yang, Y.; Lee, S. D.; Stara, J. F. (1976) Collagen and prolyl hydroxylase levels in lungs of beagles exposed to air pollutants. Environ. Res. 12: 299-305.

Osebold, J. W.; Gershwin, L. J.; Zee, Y. C. (1980) Studies on the enhancement of allergic lung sensitization by inhalation of ozone and sulfuric acid aerosol. J. Environ. Pathol. Toxicol. 3: 221-234.

Osebold, J. W.; Owens, S. L.; Zee, Y. C.; Dotson, W. M.; Labarre, D. D. (1979) Immunological alterations in the lungs of mice following ozone exposure: changes in immunoglobulin levels and antibody-containing cells. Arch. Environ. Health 34: 258-265.

Pack, A.; Hooper, M. B.; Nixon, W.; and Taylor, J. C. (1977) A computational model of pulmonary gas transport incorporating effective diffusion. Respir. Physiol. 29: 101-124.

Paiva, M. (1973) Gas transport in the human lung. J. Appl. Physiol. 35: 401-410.

Palmer, M. S.; Exley, R. W.; Coffin, D. L. (1972) Influence of pollutant gases on benzpyrene hydroxylase activity. Arch. Environ. Health 25: 439-442.

Palmer, M. S.; Swanson, D. H.; Coffin, D. L. (1971) Effect of O_3 on benzpyrene hydroxylase activity in the Syrian golden hamster. Cancer Res. 31: 730-733.

P'an, A. Y. S.; Jegier, Z. (1971) The serum trypsin inhibitor capacity during ozone exposure. Arch. Environ. Health 23: 215-219.

P'an, A. Y. S.; Jegier, Z. (1972) Trypsin protein esterase in relation to ozone-induced vascular damage. Arch. Environ. Health 24: 233-236.

P'an, A; Jegier, Z. (1976) Serum protein changes during exposure to ozone. Am. Ind. Hyg. Assoc. J. 37: 329-334.

P'an, A. Y. S.; Beland, J.; Jegier, Z. (1972) Ozone-induced arterial lesions. Arch. Environ. Health 24: 229-232.

Penha, P. D.; Werthamer, S. (1974) Pulmonary lesions induced by long-term exposure to ozone. II. Ultrastructure observations of proliferative and regressive lesions. Arch. Environ. Health 29: 282-289.

Pepelko, W. E.; Mattox, J. K.; Yang, Y. Y. (1980) Arterial blood gases, pulmonary function and pathology in rats exposed to 0.75 or 1.0 ppm ozone. J. Environ. Pathol. Toxicol. 3: 247-259.

Peterson, D. C.; Andrews, H. L. (1963) The role of ozone in radiation avoidance in the mouse. Radiat. Res. 19: 331-336.

Peterson, M. L.; Rummo, N.; House, D.; Harder, S. (1978a) The effect of ozone on human immunity: in vitro responsiveness of lymphocytes to phytohemmagglutinin. Arch. Environ. Health 36: 59-63.

Peterson, M.; Harder, S.; Rummo, N.; House, D. (1978b) Effect of ozone on leukocyte function in exposed human subjects. Environ. Res. 15: 485-493.

Phalen, R. F.; Kenoyer, J. L.; Crocker, T. T.; McClure, T. R. (1980) Effects of sulfate aerosols in combination with ozone on elimination of tracer particles inhaled by rats. J. Toxicol. Environ. Health 6: 797-810.

Plopper, C. G.; Chow, C. K.; Dungworth, D. L.; Brummer, M.; Nemeth, T. J. (1978) Effect of low level of ozone on rat lungs. II. Morphological responses during recovery and reexposure. Exp. Mol. Pathol. 29: 400-411.

Plopper, C. G.; Chow, C. K.; Dungworth, D. L.; Tyler, W. S. (1979) Pulmonary alterations in rats exposed to 0.2 and 0.1 ppm ozone: a correlated morphological and biochemical study. Arch. Environ. Health 34: 390-395.

Prat, R.; Nofre, C.; Cier, A. (1968) Effects of sodium hypochlorite, ozone, and ionizing radiations on pyrimidine constituents of Escherichia coli. Ann. Inst. Pasteur Paris 114: 595-607.

Previero, A.; Signor, A.; Bezzi, S. (1964) Tryptophan modification in polypeptide chains. Nature (London) 204: 687-688.

Pryor, W. A. (1976) Free radical reactions in biology: initiation of lipid autoxidation by ozone and nitrogen dioxide. EHP Environ. Health Perspect. 16: 180-181.

Pryor, W. A.; Dooley, M. M.; Church, D. F. (1983) Mechanisms for the reaction of ozone with biological molecules, the source of the toxic effects of ozone. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 7-19. (Advances in modern environmental toxicology: v. 5).

Pryor, W. A.; Stanley, J. P.; Blair, E; Cullen, G. B. (1976) Autoxidation of polyunsaturated fatty acids. I. Effect of ozone on the autoxidation of neat methyl linoleate and methyl linolenate. Arch. Environ. Health 31: 201-210.

Raub, J. A.; Miller, F. J.; Graham, J. A. (1983a) Effects of low-level ozone exposure on pulmonary function in adult and neonatal rats. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 363-367. (Advances in modern environmental toxicology: v. 5).

Raub, J. A.; Miller, F. J.; Graham, J. A.; Gardner, D. E.; O'Neil, J. J. (1983b) Pulmonary function in normal and elastase-treated hamsters exposed to a complex mixture of olefin-ozone-sulfur dioxide reaction products. Environ. Res. 31:302-310.

Razumovskii, S. D.; Zaikov, G. E. (1972) Effect of structure of an unsaturated compound on rate of its reaction with ozone. J. Gen. Chem. (USSR) 8: 468-472.

Reasor, M. J.; Adams III, G. K.; Brooks, J. K.; Rubin, R. J. (1979) Enrichment of albumin and IgG in the airway secretions of dogs breathing ozone. J. Environ. Sci. Health C13: 335-346.

Reddy, C. C.; Thomas, C. E.; Scholz, R. W.; Labosh, T. J.; Massaro, E. J. (1983) Effects of ozone exposure under inadequate vitamin E and/or selenium nutrition on enzymes associated with xenobiotic metabolism. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982, Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc., pp. 395-410. (Advances in modern environmental toxicology: v. 5).

Revis, N. W.; Major, T.; Dalbey, W. E. (1981) Cardiovascular effects of ozone and cadmium inhalation in the rat. In: Northrop Services, Inc., ed. Proceedings of the research planning workshop on health effects of oxidants; January 1980; Raleigh, NC. Research Triangle Park, NC: U.S. Environmental Protection Agency, Health Effects Research Laboratory; EPA-600/9-81-001; pp. 171-179. Available from: NTIS, Springfield, VA; PB81-178832.

Reynolds, R. W.; Chaffee, R. R. (1970) Studies on the combined effects of ozone and a hot environment on reaction time in subhuman primates. In: Project clean air: v. 2. Santa Barbara, CA: University of California; 8 pp; Research Project S-6.

Roehm, J.; Hadley, J. G.; Menzel, D. B. (1971a) Antioxidants vs. lung disease. Arch. Intern. Med. 128: 88-93.

Roehm, J. N., Hadley, J. G.; Menzel, D. B. (1971b) Oxidation of unsaturated fatty acids by ozone and nitrogen dioxide: a common mechanism of action. Arch. Environ. Health 23: 142-148.

Roehm, J. N.; Hadley, J. G.; Menzel, D. B. (1972) The influence of vitamin E on the lung fatty acids of rats exposed to ozone. Arch. Environ. Health 24: 237-242.

Ross, B. K.; Hlastala, M. P.; Frank, R. (1979) Lack of ozone effects on oxygen hemoglobin affinity. Arch. Environ. Health 34: 161-163.

Roth, R. P.; Tansy, M. F. (1972) Effects of gaseous air pollutants on gastric secreto-motor activities in the rat. J. Air Pollut. Control Assoc. 22: 706-709.

Roycroft, J. H.; Gunter, W. B.; Menzel, D. B. (1977) Ozone toxicity: hormone-like oxidation products from arachidonic acid by ozone-catalyzed autoxidation. Toxicol. Lett. 1: 75-82.

Sachsenmaier, W.; Siebs, W.; Tan, T. A. (1965) Wirkung von Ozon auf Mauseacitestumorzellen und auf Huknerfibroblasten in der Gewebekultur. [Effect of ozone on mouse ascites tumor cells and on chick fibroblasts in tissue culture.] Z. Krebsforsch. 67: 113-126.

Saltzman, B. E.; Gilbert, N. (1959) Iodometric microdetermination of organic oxidants and ozone. Anal. Chem. 31: 1914-1920.

Sato, S.; Kawakami, M.; Maeda, S.; Takishima, T. (1976a) Scanning electron microscopy of the lungs of vitamin E-deficient rats exposed to a low concentration of ozone. Am. Rev. Respir. Dis. 113: 809-821.

Sato, S.; Kawakami, M.; Maeda, S.; Takishima, T. (1976b) Electron microscopic studies on the effects of ozone on the lungs of vitamin E-deficient rats. Nippon Kyobu Shikkan Gakkai Zasshi 14: 355-365.

Sato, S.; Shimura, S.; Hirosa, T.; Maeda, S.; Kawakami, M.; Takishima, T.; Kimura, S. (1980) Effects of long-term ozone exposure and dietary vitamin E in rats. Tohoku J. Exp. Med. 130: 117-128.

Sato, S.; Shimura, S.; Kawakami, M.; Hirosa, T.; Maeda, S.; Takishima, T.; Kimura, S.; Yashiro, M.; Okazaki, S.; Ito, M. (1978) Biochemical and ultrastructural studies on the effects of long-term exposure of ozone on vitamin E-depleted rats. Nippon Kyobu Shikkan Gakkai Zasshi 16: 260-268.

Savino, A.; Peterson, M. L.; House, D.; Turner, A. G.; Jeffries, H. E.; Baker, R. (1978) The effects of ozone on human cellular and humoral immunity: Characterization of T and B lymphocytes by rosette formation. Environ. Res. 15: 65-69.

Scheel, L. D.; Dobrogorski, O. J.; Mountain, J. T.; Svirbely, J. L.; Stokinger, H. E. (1959) Physiologic, biochemical, immunologic and pathologic changes following ozone exposure. J. Appl. Physiol. 14: 67-80.

Scherer, P. W.; Shendalman, L. H.; Greene, N. M. (1972) Simultaneous diffusion and convection in single breath lung washout. Bull. Math. Biophys. 34: 393-412.

Scherer, P. W.; Shendalman, L. H.; Greene, N. M.; Bouhuys, A. (1975) Measurement of axial diffusivities in a model of the bronchial airways. J. Appl. Physiol. 38: 719-723.

Schlipkoter, H.; Bruch, J. (1973) Functional and morphological alterations caused by exposure to ozone. Zentralbl. Bakteriol. Parasitenkd. Infektionskr. Hyg. Abt. 1: Orig. Reihe B 156: 486-499.

Schreider, J. P.; Raabe, O. G. (1981) Anatomy of the nasal-pharyngeal airway of experimental animals. Anat. Rec. 200: 195-205.

Schwartz, L. W.; Christman, C. A. (1979) Alveolar macrophage migration. Influence of lung lining material and acute lung insult. Am. Rev. Respir. Dis. 120: 429-439.

Schwartz, L. W.; Dungworth, D. L.; Mustafa, M. G.; Tarkington, B. K.; Tyler, W. S. (1976) Pulmonary responses of rats to ambient levels of ozone: effects of 7-day intermittent or continuous exposure. Lab. Invest. 34: 565-578.

Scott, M. L. (1970) Studies on vitamin E and related factors in nutrition and metabolism. In: DeLuch, H. F.; Suttie, J. W., eds. The fat-soluble vitamins. Madison, WI: University of Wisconsin Press; pp. 355-374.

Scott, D. B. M.; Lesher, E. C. (1963) Effect of ozone on survival and permeability of *Escherichia coli*. J. Bacteriol. 85: 567-576.

Selgrade, M. J. K.; Mole, M. L.; Miller, F. J.; Hatch, G. E.; Gardner, D. E.; Hu, P. C. (1981) Effect of NO_2 inhalation and vitamin C deficiency on protein and lipid accumulation in the lung. Environ. Res. 26: 422-437.

Shakman, R. (1974) Nutritional influences on the toxicity of environmental pollutants. Arch. Environ. Health 28: 105-113.

Sherwin, R. P.; Richters, V.; Okimoto, D. (1983) Type 2 pneumocyte hyperplasia in the lungs of mice exposed to an ambient level (O_3 ppm) of ozone. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 289-297. (Advances in modern environmental toxicology: v. 5).

Shingu, H.; Sugiyama, M.; Watanabe, M.; Nakajima, T. (1980) Effects of ozone and photochemical oxidants on interferon production by rabbit alveolar macrophages. Bull. Environ. Contam. Toxicol. 24: 433-438.

Sielczak, M. W.; Denas, S. M.; Abraham, W. M. (1983) Airway cell changes in tracheal lavage of sheep after ozone exposure. J. Toxicol. Environ. Health 11: 545-553.

Sparrow, A. H.; Schairn, L. A. (1974) Mutagenic response of Tradescantia to treatment with X-rays, EMS, DBE, ozone, SO_2, N_2O and several insecticides. Am. Environ. Mutat. Soc. 445

Speit, G.; Vogel, W. (1982) The effect of sulfhydryl compounds on sister-chromatid exchanges. II. The question of cell specificity and the role of H_2O_2. Mutat. Res. 93: 175-183.

Speit, G.; Vogel, W.; Wolf, M. (1982) Characterization of sister chromatid exchange induction by hydrogen peroxide. Environ. Mutagen. 4: 135-142.

Stara, J. F.; Dungworth, D. L.; Orthoefer, J. G.; Tyler, W. S., eds. (1980) Long-term effects of air pollutants: in canine species. Cincinnati, OH: U.S. Environmental Protection Agency, Environmental Criteria and Assessment Office; EPA report no. EPA-600/8-80-014. Available from: NTIS, Springfield, VA; PB81-144875.

Stephens, R. J.; Sloan, M. F.; Groth, D. G. (1976) Effects of long-term, low level exposure of NO_2 or O_3 on rat lungs. EHP Environ. Health Perspect. 16: 178-179.

Stephens, R. J.; Freeman, G.; Stara, J. F.; Coffin, D. L. (1973) Cytologic changes in dog lungs induced by chronic exposure to ozone. Am. J. Pathol. 73: 711-726.

Stephens, R. J.; Sloan, M. F.; Evans, M. J.; Freeman, G. (1974a) Early response of lung to low levels of ozone. Am. J. Pathol. 74: 31-58.

Stephens, R. J.; Sloan, M. F.; Evans, M. J.; Freeman, G. (1974b) Alveolar type 1 cell response to exposure to 0.5 ppm O_3 for short periods. Exp. Mol. Pathol. 20: 11-23.

Stephens, R. J.; Sloan, M. F.; Groth, D. G.; Negi, D. S.; Lunan, K. D. (1978) Cytologic responses of postnatal rat lungs to O_3 or NO_2 exposure. Am. J. Pathol. 93: 183-200.

Stephens, R. J.; Buntman, D. J.; Negi, D. S.; Parkhurst, R. M.; Thomas, D. W. (1983) Tissue levels of vitamin E in the lung and the cellular response to injury resulting from oxidant gas exposure. Chest 83: 37S-39S.

Stewart, R. M.; Weir, E. K.; Montgomery, M.R.; Niewoehner (1981) Hydrogen peroxide contracts airway smooth muscle: a possible endogenous mechanism. Respir. Physiol. 45: 333-342.

Stich, H. F.; Wei, L.; Lam, P. (1978) The need for a mammalian test in Chinese hamster ovary cells by Thiol and hydrazene compounds. Mutat. Res. 68: 351-365.

Stinson, S. F.; Loosli, C. G. (1979) The effect of synthetic smog on voluntary activity of CD-1 mice. In: Animals as monitors of environmental pollutants: symposium on pathobiology of environmental pollutants, animal models and wildlife as monitors; 1977; Storrs, CT. Washington, DC: National Academy of Sciences; pp. 233-240.

Stokinger, H. E.; Wagner, W. D.; Wright, P. G. (1956) Studies on ozone toxicity. I. Potentiating effects of exercise and tolerance development. AMA Arch. Ind. Health 14: 158-162.

Stokinger, H. E.; Wagner, W. D.; Dobrogorski, O. J. (1957) Ozone toxicity studies, III. Chronic injury to lungs of animals following exposure at low level. AMA Arch. Ind. Health 16: 514-522.

Strawbridge, H. T. G. (1960) Chronic pulmonary emphysema (an experimental study). II. Spontaneous pulmonary emphysema in rabbits. Am. J. Pathol. 37: 309-331.

Suttorp, N.; Simon, L. M.; (1982) Lung cell oxidant injury. J. Clin. Invest. 70: 342-350.

Suzuki, T. (1976) Studies on the acute toxicity of 5-hydroxytryptamine in the rats pre-exposed to ozone. Bull. Tokyo Med. Dent. Univ. 23: 217-226.

Swann, H. E.; Jr,; Balchum, O. J. (1966) Biological effects of urban air pollution. Arch. Environ. Health 12:698-704.

Sweet, F.; Koo, M.-S.; Lee, S. D.; Hagar, W. L.; Sweet, W. E. (1980) Ozone selectively inhibits growth of human cancer cells. Science (Washington, DC) 209: 931-933.

Teige, B.; McManus, T. T.; Mudd, J. B. (1974) Reaction of ozone with phosphatidylcholine liposomes and the lytic effect of products on red blood cells. Chem. Phys. Lipids 12: 153-171.

Tepper, J. L.; Weiss, B.; Cox, C. (1982) Microanalysis of ozone depression of motor activity. Toxicol. Appl. Pharmacol. 64: 317-326.

Tepper, J. L.; Weiss, B.; Wood, R. W. (1983) Behavioral indices of ozone exposure. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 515-526. (Advances in modern environmental toxicology: v. 5).

Thienes, C. H., Skillen, R. G.; Hoyt, A.; Bogen, E. (1965) Effects of ozone on experimental tuberculosis and on natural pulmonary infections in mice. Am. Ind. Hyg. Assoc. J. 26: 255-260.

Thomas, G.; Fenters, J. D.; Ehrlich, R. (1979) Effect of exposure to PAN and ozone on susceptibility to chronic bacterial infection. Research Triangle Park, NC: U.S. Environmental Protection Agency, Health Effects Research Laboratory; EPA report no. EPA-600/1-79-001. Available from: NTIS, Springfield, VA; PB292267.

Thomas, G. B.; Fenters, J. D.; Ehrlich, R.; Gardner, D. E. (1981a) Effects of exposure to peroxyacetyl nitrate on susceptibility to acute and chronic bacterial infection. J. Toxicol. Environ. Health 8: 559-574.

Thomas, G. B.; Fenters, J. D.; Ehrlich, R.; Gardner, D. E. (1981b) Effects of exposure to ozone on susceptibility to experimental tuberculosis. Toxicol. Lett. 9: 11-17.

Tice, R. R.; Bender, M. A.; Ivett, J. L.; Drew, R. T. (1978) Cytogenetic effects of inhaled ozone. Mutat. Res. 58: 293-304.

Trams, E. G.; Lauter, C. J.; Brown, E. A. B.; Young, O. (1972) Cerebral cortical metabolism after chronic exposure to O_3. Arch. Environ. Health 24: 153-159.

Tremer, H. M.; Falk. H. L.; Kotin, P. (1959) Effect of air pollutants on ciliated mucous secreting epithelium. JNCI J. Natl. Cancer Inst. 23: 979-994.

Tyson, C. A.; Lunan, K. D.; Stephens, R. J. (1982) Age-related differences in GSH-shuttle enzymes in NO_2- or O_3-exposed rat lungs. Arch. Environ. Health 37: 167-176.

U.S. Department of Health, Education and Welfare (1967) The health consequences of smoking. Public Health Service Publication No. 1696, Revised January 1968. Library of Congress Catalog No. 68-60025.

U.S. Department of Health, Education, and Welfare (1969) The health consequences of smoking, 1969 Supplement. Supplement to Public Health Service Publication No. 1696-2. Library of Congress Catalog No. 68-60025.

U.S. Environmental Protection Agency. (1978) Air quality criteria for ozone and photochemical oxidants. Research Triangle Park, NC: U.S. Environmental Protection Agency, Environmental Criteria and Assessment Office; EPA-600/8-78-004. Available from: NTIS, Springfield, VA; PB80-124753.

U.S. Environmental Protection Agency. (1982) Air quality criteria for particulate matter and sulfur oxides. Research Triangle Park, NC: U.S. Environmental Protection Agency, Environmental Criteria and Assessment Office; EPA report no. EPA-600/8-82-029a.

Vaughan, T. R., Jr.; Jennelle, L. F.; Lewis, T. R. (1969) Long-term exposure to low levels of air pollutants: Effects on pulmonary function in the beagle. Arch. Environ. Health 19: 45-50.

Veninga, T. S. (1967) Toxicity of ozone in comparison with ionizing radiation. Strahlentherapie 134: 469-477.

Veninga, T. S. (1970) Ozone-induced alterations in murine blood and liver. Presented at: Second international clean air congress; December; Washington, DC. Washington, DC: International Union of Air Pollution Prevention Associations; paper no. MB-15E.

Veninga, T.; Lemstra, W. (1975) Extrapulmonary effects of ozone whether in the presence of nitrogen dioxide or not. Int. Arch. Arbeitsmed. 34: 209-220.

Veninga, T. S.; Wagenaar, J.; Lemstra, W. (1981) Distinct enzymatic responses in mice exposed to a range of low doses of ozone. EHP Environ. Health Perspect. 39: 153-157.

Verweij, H.; Van Steveninck, J. (1980) Effects of semicarbazide on processes in human red blood cell membranes. Biochim. Biophys. Acta 602: 591-599.

Verweij, H., Van Steveninck, J. (1981) Protective effects of semicarbazide and p-aminobenzoic acid against ozone toxicity. Biochem. Pharmacol. 30: 1033-1037.

Warshauer, D.; Goldstein, E.; Hoeprich, P. D.; Lippert, W. (1974) Effect of vitamin E and ozone on the pulmonary antibacterial defense mechanisms. J. Clin. Med. 83: 228-240.

Watanabe, S.; Frank, R.; Yokoyama, E. (1973) Acute effects of ozone on lungs of cats. I. Functional. Am. Rev. Respir. Dis. 108: 1141-1151.

Wayne, L. G.; Chambers, L. A. (1968). Biological effects of urban air pollution. V. A study of effects of Los Angeles atmosphere on laboratory rodents. Arch. Environ. Health 16:871-885.

Wegner, C. D. (1982) Characterization of dynamic respiratory mechanics by measurement of pulmonary and respiratory system impedance in adult bonnet monkeys (Macaca radiata): including the effects of long-term exposure to low-level ozone. Davis, CA: University of California; Ph.D. Dissertation.

Weibel, E. R. (1963) Morphometry of the human lung. New York, NY: Academic Press, Inc.

Weiss, B.; Ferin, J.; Merigan, W.; Stern, S.; Cox, C. (1981) Modification of rat operant behavior by ozone exposure. Toxicol. Appl. Pharmacol. 58: 244-251.

Wilkins, E. S.; Fettissoff, P. (1981) The effect of air pollutants on lung surfactant surface tension. J. Environ. Sci. Health A16: 477-491.

Williams, P. S.; Calabrese, E. J.; Moore, G. S. (1983a) An evaluation of the Dorset sheep as a predictive animal model for the response of G-6-PD-deficient human erythrocytes to a proposed systemic toxic ozone intermediate. J. Environ. Sci. Health A18: 1-17.

Williams, P. S.; Calabrese, E. J.; Moore, G. S. (1983b) The effect of methyl linoleate hydroperoxide (MLHP), a possible toxic intermediate of ozone, on human normal and glucose-6-phosphate dehydrogenase (G-6-PD) deficient erythrocytes. J. Environ. Sci. Health A18: 37-49.

Williams, P. S.; Calabrese, E. J.; Moore, G. S. (1983c) The effect of methyl oleate hydroperoxide, a possible toxic ozone intermediate, on human normal and glucose-6-phosphate dehydrogenase-deficient erythrocytes. Ecotoxicol. Environ. Saf. (In press).

Williams, S. J.; Charles, J. M.; Menzel, D. B. (1980) Ozone-induced alterations in phenol red absorption from the rat lung. Toxicol. Lett. 6: 213-219.

Wilmer, J. W. G. M.; Natarajan, A. T. (1981) Induction of sister-chromatid exchanges and chromosome aberrations by α-irradiated nucleic acid constituents in CHO cells. Mutat. Res. 88: 99-107.

Winterbourn, C. C. (1979) Protection by ascorbate against acetylphenylhydrazine-induced Heinz body formation in glucose-6-phosphate dehydrogenase deficient erythrocytes. Br. J. Haematol. 41: 245-252.

Witz, G.; Amoruso, M. A.; Goldstein, B. D. (1983) Effect of ozone on alveolar macrophage function: membrane dynamic properties. In: Lee, S. D.; Mustafa, M. G.; Mehlman, M. A., eds. International symposium on the biomedical effects of ozone and related photochemical oxidants; March 1982; Pinehurst, NC. Princeton, NJ: Princeton Scientific Publishers, Inc.; pp. 263-272. (Advances in modern environmental toxicology: v. 5).

Wong, D. S.; Hochstein, P. (1981) The potentiation of ozone toxicity by thyroxine. Res. Commun. Chem. Pathol. Pharmacol. 31: 483-492.

Wood, R. W. (1979) Behavioral evaluation of sensory irritation evoked by ammonia. Toxicol. Appl. Pharmacol. 50: 157-162.

World Health Organization. (1961) Chronic cor pulmonale: report of an expert committee. Geneva, Switzerland: World Health Organization. (Technical report series: no. 213).

Wright, J. L.; Lawson, L. M.; Pare, P. D.; Wiggs, B. J.; Kennedy, S.; Hogg, J. C. (1983) Morphology of peripheral airways in current smokers and ex-smokers. Am. Rev. Respir. Dis. 127: 474-477.

Xintaras, C.; Johnson, B. L.; Ulrich, C. E.; Terrill, R. E.; Sobecki, M. F. (1966) Application of the evoked response technique in air pollution toxicology. Toxicol. Appl. Pharmacol. 8: 77-87.

Yokoyama, E. (1969) A comparison of the effects of SO_2, NO_2 and O_3 on the pulmonary ventilation. Guinea pig exposure experiments. Sangyo Igaku 11: 563-568.

Yokoyama, E. (1972) The effects of O_3 on lung functions. In: Proceedings of the science lecture meeting on air pollution caused by photochemical reaction; Japan Society of Air Pollution, Tokyo; March 1972; pp. 123-143.

Yokoyama, E. (1973) The effects of low-concentration ozone on the lung pressure of rabbits and rats. Presented at: 46th annual meeting of the Japan Society of Industrial Hygiene; April; paper 223.

Yokoyama, E. (1974) On the maximal expiratory flow volume curve of rabbits exposed to ozone. Nipon Kyobu Shikkan Gakkai Zasshi 12: 556-561.

Yokoyama, E.; Frank, R. (1972) Respiratory uptake of ozone in dogs. Arch. Environ. Health 25: 132-138.

Yokoyama, E.; Ichikawa, I. (1974) Study on the biological effects of atmospheric pollutants (FY 1972-1975). In: Research report for funds of the Environmental Agency in 1974 (FY 1972-1975). Tokyo, Japan: Institute of Public Health, Department of Industrial Health; pp. 16-1 - 16-6.

Younes, M.; Siegers, C.-P. (1980) Lipid peroxidation as a consequence of glutathione depletion in rat and mouse liver. Res. Commun. Chem. Pathol. Pharm. 27: 119-128.

Yu, C. P. (1975) On equations of gas transport in the lung. Respir. Physiol. 23: 257-266.

Zelac, R. E.; Cromroy, H. L.; Bolch, Jr., W. E.; Dunavant, B. G.; Bevis, H. A. (1971a) Inhaled ozone as a mutagen. I. Chromosome aberrations induced in Chinese hamster lymphocytes. Environ. Res. 4: 262-282.

Zelac, R. E.; Cromroy, H. L.; Bolch, W. E., Jr.; Dunavant, B. G.; Bevis, H. A. (1971b) Inhaled ozone as a mutagen. II. Effect on the frequency of chromosome aberrations observed in irradiated Chinese hamsters. Environ. Res. 4: 325-342.

Zitnik, L. A.; Schwartz, L. W.; McQuillen, N. K.; Zee, Y. C.; Osebold, J. W. (1978) Pulmonary changes induced by low-level ozone: morphological observations. J. Environ. Pathol. Toxicol. 1: 365-376.

APPENDIX A: GLOSSARY OF PULMONARY TERMS AND SYMBOLS*

Acetylcholine (ACh): A naturally occurring substance in the body having important parasympathetic effects; often used as a bronchoconstrictor.

Aerosol: Solid particles or liquid droplets that are dispersed or suspended in a gas, ranging in size from 10^{-4} to 10^{2} micrometers (μm).

Air spaces: All alveolar ducts, alveolar sacs, and alveoli. To be contrasted with AIRWAYS.

Airway conductance (Gaw): Reciprocal of airway resistance. Gaw = (1/Raw).

Airway resistance (Raw): The (frictional) resistance to airflow afforded by the airways between the airway opening at the mouth and the alveoli.

Airways: All passageways of the respiratory tract from mouth or nares down to and including respiratory bronchioles. To be contrasted with AIR SPACES.

Allergen: A material that, as a result of coming into contact with appropriate tissues of an animal body, induces a state of allergy or hypersensitivity; generally associated with idiosyncratic hypersensitivities.

Alveolar-arterial oxygen pressure difference $[P(A-a)O_2]$: The difference in partial pressure of O_2 in the alveolar gas spaces and that in the systemic arterial blood, measured in torr.

Alveolar-capillary membrane: A fine membrane (0.2 to 0.4 μm) separating alveolus from capillary; composed of epithelial cells lining the alveolus, a thin layer of connective tissue, and a layer of capillary endothelial cells.

Alveolar carbon dioxide pressure (P_ACO_2): Partial pressure of carbon dioxide in the air contained in the lung alveoli.

Alveolar oxygen partial pressure (P_AO_2): Partial pressure of oxygen in the air contained in the alveoli of the lungs.

Alveolar septum (pl. septa): A thin tissue partition between two adjacent pulmonary alveoli, consisting of a close-meshed capillary network and interstitium covered on both surfaces by alveolar epithelial cells.

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*References: Bartels, H.; Dejours, P.; Kellogg, R. H.; Mead, J. (1973) Glossary on respiration and gas exchange. J. Appl. Physiol. 34: 549-558.

American College of Chest Physicians - American Thoracic Society (1975) Pulmonary terms and symbols: a report of the ACCP-ATS Joint Committee on pulmonary nomenclature. Chest 67: 583-593.

Alveolitis: (interstitial pneumonia): Inflammation of the lung distal to the terminal non-respiratory bronchiole. Unless otherwise indicated, it is assumed that the condition is diffuse. Arbitrarily, the term is not used to refer to exudate in air spaces resulting from bacterial infection of the lung.

Alveolus: Hexagonal or spherical air cells of the lungs. The majority of alveoli arise from the alveolar ducts which are lined with the alveoli. An alveolus is an ultimate respiratory unit where the gas exchange takes place.

Anatomical dead space ($V_{D\ anat}$): Volume of the conducting airways down to the level where, during air breathing, gas exchange with blood can occur, a region probably situated at the entrance of the alveolar ducts.

Arterial oxygen saturation (SaO_2): Percent saturation of dissolved oxygen in arterial blood.

Arterial partial pressure of carbon dioxide ($PaCO_2$): Partial pressure of dissolved carbon dioxide in arterial blood.

Arterial partial pressure of oxygen (PaO_2): Partial pressure of dissolved oxygen in arterial blood.

Asthma: A disease characterized by an increased responsiveness of the airways to various stimuli and manifested by slowing of forced expiration which changes in severity either spontaneously or as a result of therapy. The term asthma may be modified by words or phrases indicating its etiology, factors provoking attacks, or its duration.

Atelectasis: State of collapse of air spaces with elimination of the gas phase.

ATPS condition (ATPS): Ambient temperature and pressure, saturated with water vapor. These are the conditions existing in a water spirometer.

Atropine: A poisonous white crystalline alkaloid, $C_{17}H_{23}NO_3$, from belladonna and related plants, used to relieve spasms of smooth muscles. It is an anticholinergic agent.

Breathing pattern: A general term designating the characteristics of the ventilatory activity, e.g., tidal volume, frequency of breathing, and shape of the volume time curve.

Breuer-Hering reflexes (Hering-Breuer reflexes): Ventilatory reflexes originating in the lungs. The reflex arcs are formed by the pulmonary mechanoreceptors, the vagal afferent fibers, the respiratory centers, the medullospinal pathway, the motor neurons, and the respiratory muscles. The afferent link informs the respiratory centers of the volume state or of the rate of change of volume of the lungs. Three types of Breuer-Hering reflexes have been described: 1) an inflation reflex in which lung inflation tends to inhibit inspiration and stimulate expiration; 2) a deflation reflex in which lung deflation tends to inhibit expiration and stimulate inspiration; and 3) a "paradoxical reflex," described but largely disregarded by Breuer and Hering, in which sudden inflation may stimulate inspiratory muscles..

Bronchiole: One of the finer subdivisions of the airways, less than 1 mm in diameter, and having no cartilage in its wall.

Bronchiolitis: Inflammation of the bronchioles which may be acute or chronic. If the etiology is known, it should be stated. If permanent occlusion of the lumens is present, the term bronchiolitis obliterans may be used.

Bronchitis: A non-neoplastic disorder of structure or function of the bronchi resulting from infectious or noninfectious irritation. The term bronchitis should be modified by appropriate words or phrases to indicate its etiology, its chronicity, the presence of associated airways dysfunction, or type of anatomic change. The term chronic bronchitis, when unqualified, refers to a condition associated with prolonged exposure to nonspecific bronchial irritants and accompanied by mucous hypersecretion and certain structural alterations in the bronchi. Anatomic changes may include hypertrophy of the mucous-secreting apparatus and epithelial metaplasia, as well as more classic evidences of inflammation. In epidemiologic studies, the presence of cough or sputum production on most days for at least three months of the year has sometimes been accepted as a criterion for the diagnosis.

Bronchoconstrictor: An agent that causes a reduction in the caliber (diameter) of airways.

Bronchodilator: An agent that causes an increase in the caliber (diameter) of airways.

Bronchus: One of the subdivisions of the trachea serving to convey air to and from the lungs. The trachea divides into right and left main bronchi which in turn form lobar, segmental, and subsegmental bronchi.

BTPS conditions (BTPS): Body temperature, barometric pressure, and saturated with water vapor. These are the conditions existing in the gas phase of the lungs. For man the normal temperature is taken as 37°C, the pressure as the barometric pressure, and the partial pressure of water vapor as 47 torr.

Carbachol: A parasympathetic stimulant (carbamoylcholine chloride, $C_6H_{15}ClN_2O_2$) that produces constriction of the bronchial smooth muscles.

Carbon dioxide production ($\dot{V}CO_2$): Rate of carbon dioxide production by organisms, tissues, or cells. Common units: ml CO_2 (STPD)/kg·min.

Carbon monoxide (CO): An odorless, colorless, toxic gas formed by incomplete combustion, with a strong affinity for hemoglobin and cytochrome; it reduces oxygen absorption capacity, transport, and utilization.

Carboxyhemoglobin (COHb): Hemoglobin in which the iron is associated with carbon monoxide. The affinity of hemoglobin for CO is about 300 times greater than for O_2.

Chronic obstructive lung disease (COLD): This term refers to diseases of uncertain etiology characterized by persistent slowing of airflow during forced expiration. It is recommended that a more specific term, such as chronic obstructive bronchitis or chronic obstructive emphysema, be used whenever possible. Synonymous with chronic obstructive pulmonary disease (COPD).

Closing capacity (CC): Closing volume plus residual volume, often expressed as a ratio of TLC, i.e. (CC/TLC%).

Closing volume (CV): The volume exhaled after the expired gas concentration is inflected from an alveolar plateau during a controlled breathing maneuver. Since the value obtained is dependent on the specific test technique, the method used must be designated in the text, and when necessary, specified by a qualifying symbol. Closing volume is often expressed as a ratio of the VC, i.e. (CV/VC%).

Collateral resistance (R_{coll}): Resistance to flow through indirect pathways. See COLLATERAL VENTILATION and RESISTANCE.

Collateral ventilation: Ventilation of air spaces via indirect pathways, e.g., through pores in alveolar septa, or anastomosing respiratory bronchioles.

Compliance (C_L,C_{st}): A measure of distensibility. Pulmonary compliance is given by the slope of a static volume-pressure curve at a point, or the linear approximation of a nearly straight portion of such a curve, expressed in liters/cm H_2O or ml/cm H_2O. Since the static volume-pressure characteristics of lungs are nonlinear (static compliance decreases as lung volume increases) and vary according to the previous volume history (static compliance at a given volume increases immediately after full inflation and decreases following deflation), careful specification of the conditions of measurement are necessary. Absolute values also depend on organ size. See also DYNAMIC COMPLIANCE.

Conductance (G): The reciprocal of RESISTANCE. See AIRWAY CONDUCTANCE.

Diffusing capacity of the lung (D_L, D_LO_2, D_LCO_2, D_LCO): Amount of gas (O_2, CO, CO_2) commonly expressed as ml gas (STPD) diffusing between alveolar gas and pulmonary capillary blood per torr mean gas pressure difference per min, i.e., ml O_2/(min-torr). Synonymous with transfer factor and diffusion factor.

Dynamic compliance (C_{dyn}): The ratio of the tidal volume to the change in intrapleural pressure between the points of zero flow at the extremes of tidal volume in liters/cm H_2O or ml/cm H_2O. Since at the points of zero airflow at the extremes of tidal volume, volume acceleration is usually other than zero, and since, particularly in abnormal states, flow may still be taking place within lungs between regions which are exchanging volume, dynamic compliance may differ from static compliance, the latter pertaining to condition of zero volume acceleration and zero gas flow throughout the lungs. In normal lungs at ordinary volumes and respiratory frequencies, static and dynamic compliance are the same.

Elastance (E): The reciprocal of COMPLIANCE; expressed in cm H_2O/liter or cm H_2O/ml.

Electrocardiogram (ECG, EKG): The graphic record of the electrical currents that are associated with the heart's contraction and relaxation.

Expiratory reserve volume (ERV): The maximal volume of air exhaled from the end-expiratory level.

FEV_t/FVC: A ratio of timed ($t = 0.5, 1, 2, 3$ s) forced expiratory volume (FEV_t) to forced vital capacity (FVC). The ratio is often expressed in percent $100 \times FEV_t/FVC$. It is an index of airway obstruction.

Flow volume curve: Graph of instantaneous forced expiratory flow recorded at the mouth, against corresponding lung volume. When recorded over the full vital capacity, the curve includes maximum expiratory flow rates at all lung volumes in the VC range and is called a maximum expiratory flow-volume curve (MEFV). A partial expiratory flow-volume curve (PEFV) is one which describes maximum expiratory flow rate over a portion of the vital capacity only.

Forced expiratory flow (FEFx): Related to some portion of the FVC curve. Modifiers refer to the amount of the FVC already exhaled when the measurement is made. For example:

$FEF_{75\%}$ = instantaneous forced expiratory flow after 75% of the FVC has been exhaled.

$FEF_{200-1200}$ = mean forced expiratory flow between 200 ml and 1200 ml of the FVC (formerly called the maximum expiratory flow rate (MEFR).

$FEF_{25-75\%}$ = mean forced expiratory flow during the middle half of the FVC [formerly called the maximum mid-expiratory flow rate (MMFR)].

FEF_{max} = the maximal forced expiratory flow achieved during an FVC.

Forced expiratory volume (FEV): Denotes the volume of gas which is exhaled in a given time interval during the execution of a forced vital capacity. Conventionally, the times used are 0.5, 0.75, or 1 sec, symbolized $FEV_{0.5}$, $FEV_{0.75}$, $FEV_{1.0}$. These values are often expressed as a percent of the forced vital capacity, e.g. $(FEV_{1.0}/VC) \times 100$.

Forced inspiratory vital capacity (FIVC): The maximal volume of air inspired with a maximally forced effort from a position of maximal expiration.

Forced vital capacity (FVC): Vital capacity performed with a maximally forced expiratory effort.

Functional residual capacity (FRC): The sum of RV and ERV (the volume of air remaining in the lungs at the end-expiratory position). The method of measurement should be indicated as with RV.

Gas exchange: Movement of oxygen from the alveoli into the pulmonary capillary blood as carbon dioxide enters the alveoli from the blood. In broader terms, the exchange of gases between alveoli and lung capillaries.

Gas exchange ratio (R): See RESPIRATORY QUOTIENT.

Gas trapping: Trapping of gas behind small airways that were opened during inspiration but closed during forceful expiration. It is a volume difference between FVC and VC.

Hematocrit (Hct): The percentage of the volume of red blood cells in whole blood.

Hemoglobin (Hb): A hemoprotein naturally occurring in most vertebrate blood, consisting of four polypeptide chains (the globulin) to each of which there is attached a heme group. The heme is made of four pyrrole rings and a divalent iron (Fe^{2+}-protoporphyrin) which combines reversibly with molecular oxygen.

Histamine: A depressor amine derived from the amino acid histidine and found in all body tissues, with the highest concentration in the lung; a powerful stimulant of gastric secretion, a constrictor of bronchial smooth muscle, and a vasodilator that causes a fall in blood pressure.

Hypoxemia: A state in which the oxygen pressure and/or concentration in arterial and/or venous blood is lower than its normal value at sea level. Normal oxygen pressures at sea level are 85-100 torr in arterial blood and 37-44 torr in mixed venous blood. In adult humans the normal oxygen concentration is 17-23 ml O_2/100 ml arterial blood; in mixed venous blood at rest it is 13-18 ml O_2/100 ml blood.

Hypoxia: Any state in which the oxygen in the lung, blood, and/or tissues is abnormally low compared with that of normal resting man breathing air at sea level. If the P_{O_2} is low in the environment, whether because of decreased barometric pressure or decreased fractional concentration of O_2, the condition is termed environmental hypoxia. Hypoxia when referring to the blood is termed hypoxemia. Tissues are said to be hypoxic when their P_{O_2} is low, even if there is no arterial hypoxemia, as in "stagnant hypoxia" which occurs when the local circulation is low compared to the local metabolism.

Inspiratory capacity (IC): The sum of IRV and TV.

Inspiratory reserve volume (IRV): The maximal volume of air inhaled from the end-inspiratory level.

Inspiratory vital capacity (IVC): The maximum volume of air inhaled from the point of maximum expiration.

Kilogram-meter/min (kgm/min): The work performed each min to move a mass of 1 kg through a vertical distance of 1 m against the force of gravity. Synonymous with kilopond-meter/min.

Lung volume (V_L): Actual volume of the lung, including the volume of the conducting airways.

Maximal aerobic capacity (max $\dot{V}O_2$): The rate of oxygen uptake by the body during repetitive maximal respiratory effort. Synonymous with maximal oxygen consumption.

Maximum breathing capacity (MBC): Maximal volume of air which can be breathed per minute by a subject breathing as quickly and as deeply as possible. This tiring lung function test is usually limited to 12-20 sec, but given in liters (BTPS)/min. Synonymous with maximum voluntary ventilation (MVV).

Maximum expiratory flow ($\dot{V}_{max\ x}$): Forced expiratory flow, related to the total lung capacity or the actual volume of the lung at which the measurement is made. Modifiers refer to the amount of lung volume remaining when the measurement is made. For example:

$\dot{V}_{max\ 75\%}$ = instantaneous forced expiratory flow when the lung is at 75% of its TLC.

$\dot{V}_{max\ 3.0}$ = instantaneous forced expiratory flow when the lung volume is 3.0 liters

Maximum expiratory flow rate (MEFR): Synonymous with $FEF_{200-1200}$.

Maximum mid-expiratory flow rate (MMFR or MMEF): Synonymous with $FEF_{25-75\%}$.

Maximum ventilation (max $\dot{V}_E$): The volume of air breathed in one minute during repetitive maximal respiratory effort. Synonymous with maximum ventilatory minute volume.

Maximum voluntary ventilation (MVV): The volume of air breathed by a subject during voluntary maximum hyperventilation lasting a specific period of time. Synonymous with maximum breathing capacity (MBC).

Methemoglobin (MetHb): Hemoglobin in which iron is in the ferric state. Because the iron is oxidized, methemoglobin is incapable of oxygen transport. Methemoglobins are formed by various drugs and occur under pathological conditions. Many methods for hemoglobin measurements utilize methemoglobin (chlorhemiglobin, cyanhemiglobin).

Minute ventilation ($\dot{V}_E$): Volume of air breathed in one minute. It is a product of tidal volume (V_T) and breathing frequency (f_B). See VENTILATION.

Minute volume: Synonymous with minute ventilation.

Mucociliary transport: The process by which mucus is transported, by ciliary action, from the lungs.

Mucus: The clear, viscid secretion of mucous membranes, consisting of mucin, epithelial cells, leukocytes, and various inorganic salts suspended in water.

Nasopharyngeal: Relating to the nose or the nasal cavity and the pharynx (throat).

Nitrogen oxides: Compounds of N and O in ambient air; i.e., nitric oxide (NO) and others with a higher oxidation state of N, of which NO_2 is the most important toxicologically.

Nitrogen washout (ΔN_2, dN_2): The curve obtained by plotting the fractional concentration of N_2 in expired alveolar gas vs. time, for a subject switched from breathing ambient air to an inspired mixture of pure O_2. A progressive decrease of N_2 concentration ensues which may be analyzed into two or more exponential components. Normally, after 4 min of pure O_2 breathing the fractional N_2 concentration in expired alveolar gas is down to less than 2%.

Normoxia: A state in which the ambient oxygen pressure is approximately 150 ± 10 torr (i.e., the partial pressure of oxygen in air at sea level).

Oxidant: A chemical compound that has the ability to remove, accept, or share electrons from another chemical species, thereby oxidizing it.

Oxygen consumption ($\dot{V}O_2$, $\dot{Q}O_2$): Rate of oxygen uptake of organisms, tissues, or cells. Common units: ml O_2 (STPD)/(kg·min) or ml O_2 (STPD)/(kg·hr). For whole organisms the oxygen consumption is commonly expressed per unit surface area or some power of the body weight. For tissue samples or isolated cells $\dot{Q}_{O2}$ = µl O_2/hr per mg dry weight.

Oxygen saturation (SO_2): The amount of oxygen combined with hemoglobin, expressed as a percentage of the oxygen capacity of that hemoglobin. In arterial blood, SaO_2.

Oxygen uptake ($\dot{V}O_2$): Amount of oxygen taken up by the body from the environment, by the blood from the alveolar gas, or by an organ or tissue from the blood. When this amount of oxygen is expressed per unit of time one deals with an "oxygen uptake rate." "Oxygen consumption" refers more specifically to the oxygen uptake rate by all tissues of the body and is equal to the oxygen uptake rate of the organism only when the O_2 stores are constant.

Particulates: Fine solid particles such as dust, smoke, fumes, or smog, found in the air or in emissions.

Pathogen: Any virus, microorganism, or etiologic agent causing disease.

Peak expiratory flow (PEF): The highest forced expiratory flow measured with a peak flow meter.

Peroxyacetyl nitrate (PAN): Pollutant created by action of UV component of sunlight on hydrocarbons and NO_x in the air; an ingredient of photochemical smog.

Physiological dead space (V_D): Calculated volume which accounts for the difference between the pressures of CO_2 in expired and alveolar gas (or arterial blood). Physiological dead space reflects the combination of anatomical dead space and alveolar dead space, the volume of the latter increasing with the importance of the nonuniformity of the ventilation/perfusion ratio in the lung.

Plethysmograph: A rigid chamber placed around a living structure for the purpose of measuring changes in the volume of the structure. In respiratory measurements, the entire body is ordinarily enclosed ("body plethysmograph") and the plethysmograph is used to measure changes in volume of gas in the system produced 1) by solution and volatilization (e.g., uptake of foreign gases into the blood), 2) by changes in pressure or temperature (e.g., gas compression in the lungs, expansion of gas upon passing into the warm, moist lungs), or 3) by breathing through a tube to the outside. Three types of plethysmograph are used: a) pressure, b) volume, and c) pressure-volume. In type a, the body chambers have fixed volumes and volume changes are measured in terms of pressure change secondary to gas compression (inside the chamber, outside the body). In type b, the body chambers serve essentially as conduits between the body surface and devices (spirometers or integrating flowmeters) which measure gas displacements. Type c combines a and b by appropriate summing of chamber pressure and volume displacements.

Pneumotachograph: A device for measuring instantaneous gas flow rates in breathing by recording the pressure drop across a fixed flow resistance of known pressure-flow characteristics, commonly connected to the airway by means of a mouthpiece, face mask, or cannula. The flow resistance usually consists either of parallel capillary tubes (Fleisch type) or of fine-meshed screen (Silverman-Lilly type).

Pulmonary alveolar proteinosis: A chronic or recurrent disease characterized by the filling of alveoli with an insoluble exudate, usually poor in cells, rich in lipids and proteins, and accompanied by minimal histologic alteration of the alveolar walls.

Pulmonary edema: An accumulation of excessive amounts of fluid in the lung extravascular tissue and air spaces.

Pulmonary emphysema: An abnormal enlargement of the air spaces distal to the terminal nonrespiratory bronchiole, accompanied by destructive changes of the alveolar walls. The term emphysema may be modified by words or phrases to indicate its etiology, its anatomic subtype, or any associated airways dysfunction.

Residual volume (RV): That volume of air remaining in the lungs after maximal exhalation. The method of measurement should be indicated in the text or, when necessary, by appropriate qualifying symbols.

Resistance flow (R): The ratio of the flow-resistive components of pressure to simultaneous flow, in cm H_2O/liter per sec. Flow-resistive components of pressure are obtained by subtracting any elastic or inertial components, proportional respectively to volume and volume acceleration. Most flow resistances in the respiratory system are nonlinear, varying with the magnitude and direction of flow, with lung volume and lung volume history, and possibly with volume acceleration. Accordingly, careful specification of the conditions of measurement is necessary; see AIRWAY RESISTANCE, TISSUE RESISTANCE, TOTAL PULMONARY RESISTANCE, COLLATERAL RESISTANCE.

Respiratory cycle: A respiratory cycle is constituted by the inspiration followed by the expiration of a given volume of gas, called tidal volume. The duration of the respiratory cycle is the respiratory or ventilatory period, whose reciprocal is the ventilatory frequency.

Respiratory exchange ratio: See RESPIRATORY QUOTIENT.

Respiratory frequency (f_R): The number of breathing cycles per unit of time. Synonymous with breathing frequency (f_B).

Respiratory quotient (RQ, R): Quotient of the volume of CO_2 produced divided by the volume of O_2 consumed by an organism, an organ, or a tissue during a given period of time. Respiratory quotients are measured by comparing the composition of an incoming and an outgoing medium, e.g., inspired and expired gas, inspired gas and alveolar gas, or arterial and venous blood. Sometimes the phrase "respiratory exchange ratio" is used to designate the ratio of CO_2 output to the O_2 uptake by the lungs, "respiratory quotient" being restricted to the actual metabolic CO_2 output and O_2 uptake by the tissues. With this definition, respiratory quotient and respiratory exchange ratio are identical in the steady state, a condition which implies constancy of the O_2 and CO_2 stores.

Shunt: Vascular connection between circulatory pathways so that venous blood is diverted into vessels containing arterialized blood (right-to-left shunt, venous admixture) or vice versa (left-to-right shunt). Right-to-left shunt within the lung, heart, or large vessels due to malformations are more important in respiratory physiology. Flow from left to right through a shunt should be marked with a negative sign.

Specific airway conductance (SGaw): Airway conductance divided by the lung volume at which it was measured, i.e., normalized airway conductance. SGaw = Gaw/TGV.

Specific airway resistance (SRaw): Airway resistance multiplied by the volume at which it was measured. SRaw = Raw x TGV.

Spirograph: Mechanical device, including bellows or other scaled, moving part, which collects and stores gases and provides a graphical record of volume changes. See BREATHING PATTERN, RESPIRATORY CYCLE.

Spirometer: An apparatus similar to a spirograph but without recording facility.

Static lung compliance (C_{Lst}): Lung compliance measured at zero flow (breath-holding) over linear portion of the volume-pressure curve above FRC. See COMPLIANCE.

Static transpulmonary pressure (P_{st}): Transpulmonary pressure measured at a specified lung volume; e.g., P_{st}TLC is static recoil pressure measured at TLC (maximum recoil pressure).

Sulfur dioxide (SO_2): Colorless gas with pungent odor, released primarily from burning of fossil fuels, such as coal, containing sulfur.

STPD conditions (STPD): Standard temperature and pressure, dry. These are the conditions of a volume of gas at 0°C, at 760 torr, without water vapor. A STPD volume of a given gas contains a known number of moles of that gas.

Surfactant, pulmonary: Protein-phospholipid (mainly dipalmitoyl lecithin) complex which lines alveoli (and possibly small airways) and accounts for the low surface tension which makes air space (and airway) patency possible at low transpulmonary pressures.

Synergism: A relationship in which the combined action or effect of two or more components is greater than the sum of effects when the components act separately.

Thoracic gas volume (TGV): Volume of communicating and trapped gas in the lungs measured by body plethysmography at specific lung volumes. In normal subjects, TGV determined at end expiratory level corresponds to FRC.

Tidal volume (TV): That volume of air inhaled or exhaled with each breath during quiet breathing, used only to indicate a subdivision of lung volume. When tidal volume is used in gas exchange formulations, the symbol V_T should be used.

Tissue resistance (R_{ti}): Frictional resistance of the pulmonary and thoracic tissues.

Torr: A unit of pressure equal to 1,333.22 dynes/cm^2 or 1.33322 millibars. The torr is equal to the pressure required to support a column of mercury 1 mm high when the mercury is of standard density and subjected to standard acceleration. These standard conditions are met at 0°C and 45° latitude, where the acceleration of gravity is 980.6 cm/sec^2. In reading a mercury barometer at other temperatures and latitudes, corrections, which commonly exceed 2 torr, must be introduced for these terms and for the thermal expansion of the measuring scale used. The torr is synonymous with pressure unit mm Hg.

Total lung capacity (TLC): The sum of all volume compartments or the volume of air in the lungs after maximal inspiration. The method of measurement should be indicated, as with RV.

Total pulmonary resistance (R_L): Resistance measured by relating flow-dependent transpulmonary pressure to airflow at the mouth. Represents the total (frictional) resistance of the lung tissue (R_{ti}) and the airways (Raw). $R_L = R_{aw} + R_{ti}$.

Trachea: Commonly known as the windpipe; a cartilaginous air tube extending from the larynx (voice box) into the thorax (chest) where it divides into left and right branches.

Transpulmonary pressure (P_L): Pressure difference between airway opening (mouth, nares, or cannula opening) and the visceral pleural surface, in cm H_2O. Transpulmonary in the sense used includes extrapulmonary structures, e.g., trachea and extrathoracic airways. This usage has come about for want of an anatomic term which includes all of the airways and the lungs together.

Ventilation: Physiological process by which gas is renewed in the lungs. The word ventilation sometimes designates ventilatory flow rate (or ventilatory minute volume) which is the product of the tidal volume by the ventilatory frequency. Conditions are usually indicated as modifiers; i.e.,

$\dot{V}_E$ = Expired volume per minute (BTPS),
and
$\dot{V}_E$ = Inspired volume per minute (BTPS).

Ventilation is often referred to as "total ventilation" to distinguish it from "alveolar ventilation" (see VENTILATION, ALVEOLAR)

Ventilation, alveolar ($\dot{V}_A$): Physiological process by which alveolar gas is completely removed and replaced with fresh gas. Alveolar ventilation is less than total ventilation because when a tidal volume of gas leaves the alveolar spaces, the last part does not get expelled from the body but occupies the dead space, to be reinspired with the next inspiration. Thus the volume of alveolar gas actually expelled completely is equal to the tidal volume minus the volume of the dead space. This truly complete expiration volume times the ventilatory frequency constitutes the alveolar ventilation.

Ventilation, dead-space ($\dot{V}_D$): Ventilation per minute of the physiologic dead space (wasted ventilation), BTPS, defined by the following equation:

$$\dot{V}_D = \dot{V}_E(PaCO_2 - P_ECO_2)/(PaCO_2 - P_ICO_2)$$

Ventilation/perfusion ratio ($\dot{V}_A/\dot{Q}$): Ratio of the alveolar ventilation to the blood perfusion volume flow through the pulmonary parenchyma. This ratio is a fundamental determinant of the O_2 and CO_2 pressure of the alveolar gas and of the end-capillary blood. Throughout the lungs the local ventilation/perfusion ratios vary, and consequently the local alveolar gas and end-capillary blood compositions also vary.

Vital capacity (VC): The maximum volume of air exhaled from the point of maximum inspiration.